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ROTOR-BEARING DYNAMICS
TECHNOLOGY DESIGN GUIDE
Part I Flexible Rotor Dynamics

SHAKER RESEARCH CORP.
BALLSTON LAKE, NEW YORK 12019

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WRIGHT-PATTERSON AIR FORCE BASE, OHIO 45433

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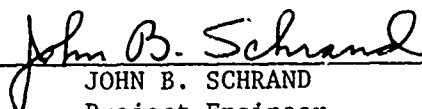
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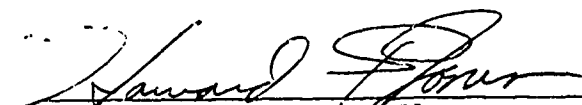
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This technical report has been reviewed and is approved for publication.


JOHN B. SCHRAND
Project Engineer


HOWARD F. JONES
Chief, Lubrication Branch

FOR THE COMMANDER


ROBERT D. SHERRILL
Acting Chief, Fuels and Lubrication Division

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20. ABSTRACT (Cont'd)

stations, the capability to utilize a small subset of these stations in much of the calculations, a set of bearing characteristics that depend on rotor speed and vibration frequency and that include anisotropy and damping, and an economical combination of a separate rotor analysis and the characteristics of the bearings. The report includes: an introduction to use of the program as well as a detailed user's manual, The report also includes both an overview of the mathematical basis of the program and a complete presentation of those mathematics.

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FOREWORD

This report was prepared by Shaker Research Corporation under USAF Contract No. AF33615-76-C-2038. The contract was initiated under Project 304B, "Fuels, Lubrication, and Fire Protection," Task 304806, "Aerospace Lubrication," Work Unit 30480685, "Rotor-Bearing Dynamics Design."

The work reported herein was performed during the period 15 April 1976 to 15 November 1979, under the direction of John B. Schrand (AFWAL/POSL) and Dr. James F. Dill (AFWAL/POSL), Project Engineers. The report was released by the authors in November 1979.

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NOMENCLATURE

<u>Symbol</u>	<u>Description</u>
a	Denotes a constant
$\underline{a}$	Defined by Equations (5.9)
A	Denotes a constant
$\underline{A}$	Mobility matrix
$\underline{B}$	Damping matrix
C	Denotes a constant
c_α	Modal damping coefficient
$\underline{C}$	Defined by Equations (5.50)
$\underline{\underline{C}}$	Torsional and lateral connection matrices (Equations (5.17) and (5.56))
d	Mass diameter
D	Stiffness diameter
E	Young's modulus
F	External force on rotor
g	Gravitational constant
G	Shear modulus
$\vec{H}$	Angular momentum vector
i	$\sqrt{-1}$
$\vec{i}$	unit vector
$\underline{I}$	Identity matrix
I	Area or mass moment of inertia
$\mathcal{I}$	Inertia tensor
$\underline{\underline{I}}$	Defined by Equation (A-3)

NOMENCLATURE (Continued)

<u>Symbol</u>	<u>Description</u>
$\vec{j}$	Unit vector
J	Area polar moment of inertia
J	Transverse mass moment of inertia
$\vec{k}$	Unit vector
k	Lineal spring rate
$\underline{K}$	Stiffness matrix or impedance matrix
K_n	Second derivative in cubic spline
ρ	Length between supports of simple rigid rotor or length of a shaft segment
L	Length of simple rigid rotor
m	Mass
M	External moment on rotor, internal bending moment in rotor
M	Rigid body inertia
$\underline{P}$	Force vector
$\underline{Q}$	Torsional or flexural primitive vector
$\vec{R}$	Position vector
$\underline{R}$	Bearing reaction force vector
R	Ellipse radius (major or minor)
s	Slope of deflected rotor
$\underline{S}$	Defined by Equations (5.9) and (5.50)
$\underline{T}$	Intersegment or intrasegment connection matrix
t	Time

NOMENCLATURE (Continued)

<u>Symbol</u>	<u>Description</u>
u	Real part of eigenvalue
v	Imaginary part of eigenvalue
V	Shear force in rotor
w	Displacement in whirl coordinates
W	Determinant (Defined by Equation 6.7).
$\underline{w}$	Defined by Equations (5.50)
$\underline{\underline{W}}$	Whirl coordinate transformation matrix
x	Vertical coordinate system axis
$\underline{x}$	Displacement vector
y	Horizontal coordinate system axis
z	Rotor spin axis
$\underline{\underline{Z}}$	Dynamic stiffness (impedance) matrix
α	Inclination angle of orbit ellipse, modal subscript
β	Defined by Equation (5.42)
γ	Defined by Equation (5.7)
δ	Displacement of rotor center, distance from rotor center to mass center, denotes variation of a quantity
Δ	axial offset of rigid body inertia
ϵ	Magnitude of error
ζ	Defined by Equation (5.48)
θ	Euler angle, shaft slope, first derivative in cubic spline
$\underline{\underline{\Theta}}$	Coordinate transformation matrix
κ	Eigenvalue or constant in eigenvalue problem

NOMENCLATURE (Continued)

<u>Symbol</u>	<u>Description</u>
ν	Frequency of vibration
ρ	Density of rotor material
σ	Defined by Equations (5.11) and (5.52)
ϕ	Shaft twist about z axis, Euler angle
$\underline{\phi}$	Defined by Equations (5.9)
$\underline{\underline{\phi}}$	Coordinate transformation matrix
ψ	Euler angle
$\underline{\underline{\psi}}$	Coordinate transformation matrix
ω	Angular velocity component, rotor speed
$\vec{\omega}$	Angular velocity vector

Subscripts

1, 2, etc.	Denotes elements of a vector, distinguishes among constants
1, 2	Denotes major and minor axes
b	Denotes bearing
f	Denotes flexure
i	Inner diameter
i, j	Denotes elements of a matrix
J	Denotes bearing station number
K	Denotes segment
M	Total number of segments used to model rotor
u	Denotes arbitrary interval in cubic spline or second derivative
N	Denotes bearing station number and number of intervals in cubic spline

NOMENCLATURE (Continued)

<u>Subscripts</u>	<u>Description</u>
o	Outer diameter, equilibrium (unperturbed) condition
p	Denotes pedestal or polar
t	Denotes torsion or transverse
x, y	Denotes z-x and z-y planes respectively
x, y, z	Denote Cartesian components of a vector
xy, xx, yx, yy	Denote elements of stiffness and damping matrices
$, \perp$	Defined in Equation (5.96)
α	Denotes a modal quantity
<u>Superscripts</u>	
()'	Denotes perturbation, denotes estimate, refers quantity to an associated coordinate system, denotes derivative; or refers to right end of a segment
()', ()''	Refers quantity to associated coordinate systems, or denotes derivative
($\cdot$)	Forward (corotational whirl)
($\cdot$)	Backward (counter rotational whirl)
($\wedge$)	Either forward or backward whirl
() ⁻¹	Denotes inverse of matrix
($\dot{}$)	Differentiation with respect to time

SECTION I
INTRODUCTION

The practice of employing numerical computation to study vibrations of machinery has become a reality since Holzer's classical work in 1921 [1]. Understandably, during the earlier days when electronic digital computation equipment was not available, only the relatively simple torsional problem was considered. Two decades passed, when Myklestad's treatment of the lateral vibrations of a beam-like structure [2] was first formulated to study airplane wings. This important event took place when many of the finest minds in the history of modern technology were devoted to the engineering of the earthbound flying machine. It was rather remarkable that this development took place at all when digital computing equipment was of the electro-mechanical type and its memory capacity was mainly limited to a single register. Although the fundamental matrix methods were already available, their execution was done literally by hand, including the process of recording intermediate numbers. Adaptations of Myklestad's method to calculate critical speeds of a flexible rotor was soon proposed by Prohl [3]. By this time, most of the important elements in the computation methodology of machinery vibration were fully established. In the following years, the technological impacts of modern, high speed, digital, electronic computers were felt in all phases of engineering activities. Use of such computers in rotor dynamics studies is now routine. Engineers of the present generation are unburdened of the drudgery of computation chores.

The peculiar role of fluid-film bearings in the dynamics of a high speed rotor was first expounded by Newkirk in the mid 20's [4, 5]. Since then, journal bearing related instability of a rotor received attention from many investigators [6, 7, 8]. Designation of elastic and damping properties to study oil-film journal bearing effects on rotor vibrations was formally proposed by Hagg and Sankey [9]. In this respect, due to cross-coupling and anisotropic effects, dynamics of a rotor-bearing system assumed a higher degree of complexity than other problems of linear vibration in both physical concepts and computation procedures. Since relatively small lateral motion may represent a large fraction of the

radial clearance of a fluid-film bearing, interests in non-linear bearing effects soon developed. Unfortunately, only specialized topics in non-linear mechanics can be treated with any degree of thoroughness [10, 11, 12, 13]. Many attempted to utilize direct integration to study transient problems of rotor dynamics. Effectiveness of the latter approach is still a matter of much controversy. Lack of total success in its advocacy may be attributed to the following:

- o Numerical algorithms for direct integration require attention to control truncation error to avoid numerical instability. Proper implementation of this method to a realistic problem is generally quite costly.
- o Unless addressed to solve a problem for which some non-linear feature of the system is particularly prominent, the results of integration are disappointingly inconsequential. It is actually quite difficult to identify a worthy non-linear problem.
- o Uncertainties in the operating conditions of the fluid-film bearing (e.g. bearing clearance, lubricant temperature, and effects of feeding) often over-shadow improvement of accuracy which may be related to non-linear effects.

While earlier studies of dynamic fluid-film properties were restricted to rigid body motions of the rotor, a major step forward in the technology of rotor-bearing dynamics was advanced when a series of technical reports and associated computer software were published under the sponsorship of the Air Force Aero-Propulsion Laboratory, Wright-Patterson Air Force Base. This set of documents, known as Rotor-Bearing Dynamics Design Technology AFAPL-TR-65-45, consists of ten technical reports and ten computer programs, which are respectively listed in Tables 1 and 2. Within the realm of a linear characterization of the support bearings, the flexible rotor can thus be analyzed not only to obtain the critical speed characteristics, but also to predict unbalance response, stability threshold, and parametric excitation with allowances for cross-coupling

TABLE 1

TECHNICAL REPORTS
CURRENT ROTOR-BEARING DYNAMICS DESIGN TECHNOLOGY
SERIES AFAPL-TR-65-45

<u>PART NO.</u>	<u>PART SUB-TITLE</u>	<u>AD NO.</u>
I	State-of-the-Art	466390
II	Rotor Stability Theory	466391
III	Design Handbook for Fluid Film Bearings	466392
IV	Ball Bearing Design Manual	466393
V	Computer Program Manual for Rotor Response and Stability	470315
VI	The Influence of Electro- magnetic Forces on the Stability and Response of an Alternator Rotor	822401
VII	The Three Lobe Bearing and Floating Ring Bearing	829895
VIII	Spiral Grooved Floating Ring Journal Bearing	852998
IX	Thrust Bearing Effects on Rotor Stability	872980
X	Feasibility Study of Electro- magnetic Means to Improve the Stability of Rotor Bearing Systems	869324

NOTE: A typical example identifying a part is:

AFAPL-TR-65-45, Part I, "Rotor Bearing Dynamics Design Technology,
State-of-the-Art", AD No. 466390.

TABLE 2

COMPUTER PROGRAMS

CURRENT ROTOR-BEARING DYNAMICS DESIGN TECHNOLOGY SERIES
AFAPL-TR-65-45

<u>PART NO.</u>	<u>PROGRAM USE</u>	<u>AFAPL/SFL PROGRAM NO.</u>
V	Rotor Stability	100
V	Rotor Unbalance Response	101
IV	Static Ball Bearing	102
VI	Rotor Response with EMF	103
VI	Rotor Stability with EMF	104
VII	Hybrid Journal Bearing Performance	105
VII	Three Lobe Bearing	106
VIII	Floating Ring with Herringbone	106
VIII	Herringbone Journal Bearing	108
IX	Rotor Stability with Thrust Bearing	117

and anisotropy. Throughout the passing years, this approach for rotor dynamics analysis has gained widespread acceptance. In the meantime, some new trends of technological development evolved; an improved analytical treatment of non-conservative (damped) rotor-bearing systems became known [14], and understanding of users' interests (of Rotor-Bearing Dynamics Design Technology) increased through experience.

As a part of an ongoing contract with the Air Force Aero-Propulsion Laboratory to update the Rotor-Bearing Dynamics Design Technology, this report covers the topic of Flexible Rotor-Bearing Dynamics. It will supersede the reports AFAPL-TR-65-45, Parts V and IX (AD No. 470315 and 872980), and the computer program described in Section III will replace AFAPL-SFL Programs No. 100, 101, and 117.

Essential improvements over the original version include the following:

- o Distributed analysis is used. User is not required to subdivide a long uniform shaft segment to control accuracy.
- o Local inclination (shaft slope) may be designated as an independent degree of freedom (in addition to deflection) in the lateral shaft motion.
- o Both angular and lineal stiffness and damping coefficients may be assigned to each bearing.
- o Vibration frequency may be specified by the user to be different from the shaft rotational rate.
- o Effects of bearing modification and/or relocation can be studied with a single input setup.
- o Condition of stability is established for all natural modes in a user specified frequency range. Quantitative indication of the stability condition is expressed in terms of the critical damping ratio of each natural mode.

- o Forcing function can be designated as a force system and/or a moment system at each external-excitation station.
- o The forcing function can be either stationary or rotating.
- o In a damped response analysis, the damped resonance is automatically searched for within the specified frequency range.

Section II contains a description of the capabilities of the new rotor dynamics computer program. Section III is the User's Manual, including instructions and examples. An overview of the theory upon which the program is based is given in Section IV. The theory itself is presented in Section V, which contains complete derivations of the analytical basis of the program. Section VI gives attention to the special eigenvalue analyses employed in the new program. A derivation of the small inclination gyroscopic d'Alembert effect is included as Appendix A because there is no other convenient reference for this information. Appendix B covers the various uses of the spline curve-fitting scheme, which is employed in the real and the complex eigenvalue algorithms. Appendix C contains the listing of the source program in FORTRAN.

SECTION II

ROTOR DYNAMIC ANALYSIS AND CAPABILITIES OF THE COMPUTER PROGRAM

The primary objective in the performance of rotordynamic analysis is to establish whether or not conditions of hazardous vibrations can develop to threaten the safe operation of the machine. The analysis presented in this report and the accompanying software cover synchronous and asynchronous passive responses as well as self-excited shaft whirls.

Figure 1 illustrates the role of rotordynamic analysis in a typical rotor engineering effort. In this diagram, the total analysis effort is divided into three steps. Step I analysis deals with the determination of potential resonances with obvious excitation sources; e.g., mass unbalance and gear mesh compliance. This is the minimum step which should be carried out in the evaluation of every new design. Generous variations in bearing support stiffness estimation should be allowed since the resonance frequencies of the lower modes can be quite sensitive to the precise values of the support stiffnesses. If little likelihood of resonance is revealed, subsequent steps of analysis may not be necessary. If undesirable resonances are uncovered, consideration should be given to alterations of shafting construction, bearing sizing, and/or bearing relocation to separate the applicable natural frequencies and speed-related excitations. Step II analysis would be performed when near-resonances appear to be unavoidable. Damped response amplitudes are sought. Complete characterization of the bearing supports should be incorporated, including damping coefficients and pedestal compliance where applicable. Balancing limits should be accordingly established to ensure ample safety margins. Step III analysis deals in part with self-excited shaft whirls. Various "obscure" factors can cause self-excited shaft whirls; the most commonly known one is the cross-coupling effect of fluid-film bearings. The need to perform Step III analysis largely depends on past experience with similar designs. It is necessary to be able to characterize with sufficient realism the relevant excitation sources to make this analysis meaningful. One should particularly pay attention to induced forces

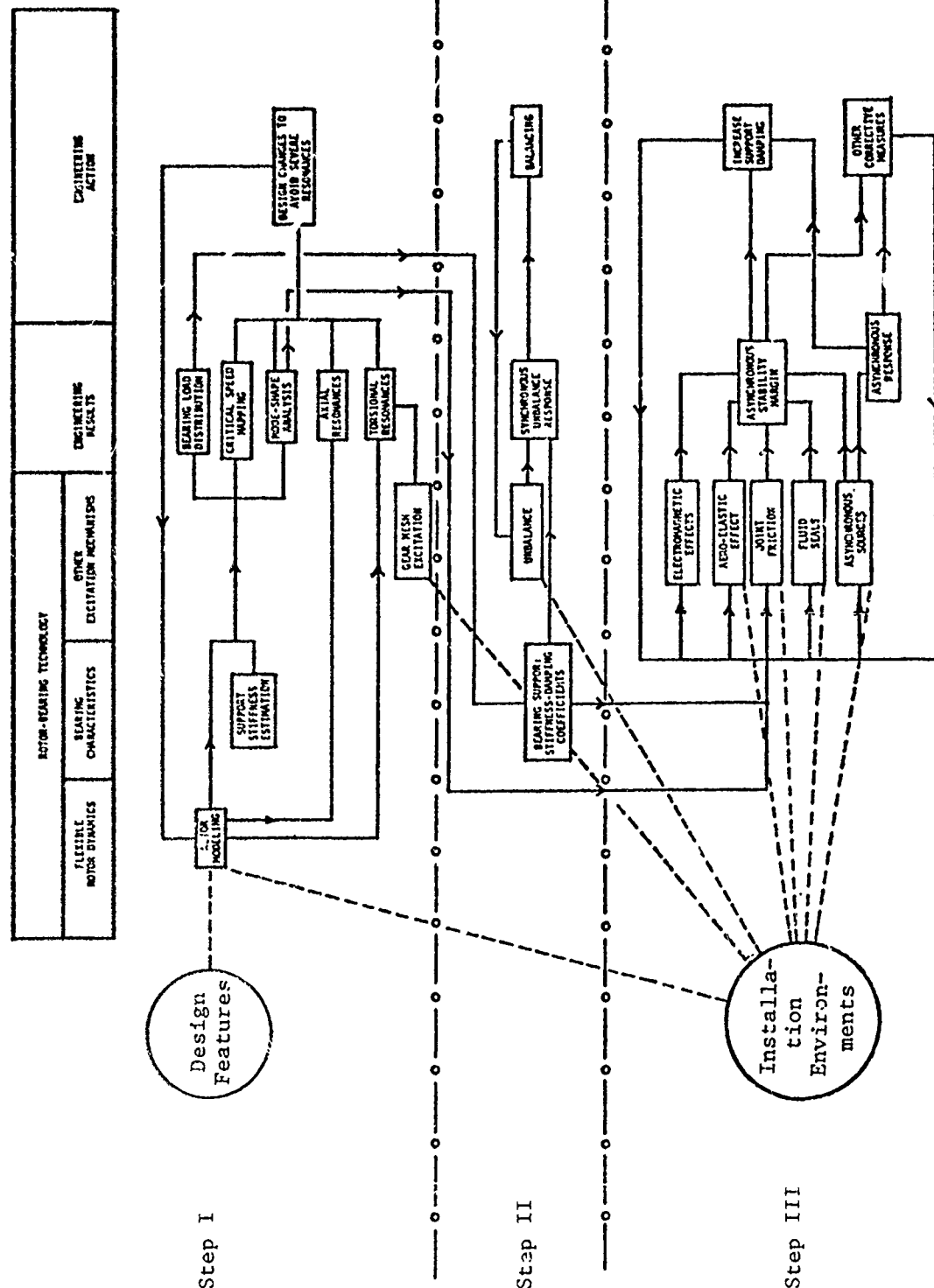


Figure 1 Steps in a Complete Rotordynamics Analysis Procedure

associated with small clearance impellers, flow leakage seals, and conditions of magnetic gap.

The computer program described in this report enables the user to perform all the rotordynamics analyses mentioned above. In addition, the program has unique capabilities that allow the user to "customize" his analysis to address the topics of greatest interest. In the remainder of this section, a general description of the capabilities of the program are given. The material in this section, plus that in Section III (which is the "User's Manual"), should be sufficient for use of the program. The reader is referred to Section IV for a more detailed discussion of the topics covered in the present section. The mathematical foundations for both sections are given in Section V, VI and in Appendices A and B.

2.1 Modelling of the Rotor

The rotor is modelled for the dynamic analyses by dividing it into numerous segments. Typically, the segments will lie between cross-sections where changes in shaft diameter or shaft material occur. In addition, segment length will be determined by the location and size of impeller/turbine-discs, or be terminated at places along the rotor length where excitation forces can be imposed or vibration displacements are of interest. It should be noted that the analytical basis of the program employs, within each segment, the exact bending solution for a constant cross-section beam. As a result, the user need not subdivide such portions of the rotor for increased accuracy. This characteristic is one of the features of the program.

Stations are cross-sections along the rotor where segments join. Stations not only locate all segment connections, but also locate bearings, excitation points, points for displacement results, and points of reference for representing rigid body inertias. Although the user must define sufficient stations to describe his rotor, the analysis procedure does not have to work continuously with all of the stations employed. The

user will typically select a subset of these stations when his program is run. This subset (called the "action" or "excitation" stations) will include only those stations at which

- o bearing damping or bearing anisotropy are to be considered
- o bearings are to be added, removed, or have stiffness values change with speed or frequency
- o excitation forces or moments are to be applied
- o the results obtained for the motions of the rotor are desired.

The size of this subset of rotor stations influences the computer time required for completing the analysis of the rotordynamics. Because the size of the subset typically will be much smaller than that used in representing the rotor, significant computer economy can be achieved. The ability to employ only a few such stations is another of the features of the program.

2.2 Representing the Operational Speed and Frequency Range

The computer program employs a frequency domain, forced response rotor dynamics analysis. In this, the results obtained for critical speeds, response, stability, etc., are based on separate calculations made at discrete vibration frequencies and associated rotor rotational speeds. The user is required to specify these speeds and frequencies. Most generally, he can direct the program to employ a number of rotor speeds and, at each speed, to employ a number of frequencies. (For critical speed and unbalance response calculations, the situation is simple since each speed is associated with an identical frequency). The results obtained will be dependant on the speed-frequency choice. The rotor speeds must be those at which the rotor will run or must cover the range in which vibrational problems occur. The frequencies must likewise cover the range in which vibrational problems occur. For example, in a critical speed calculation, the frequency range (and associated rotor speed range) defines the frequency limits within which the criticals will be found. In a stability analysis calculation, the frequency range (at a given rotor speed) defines the frequency limits within which an unstable mode can be found.

Because the method of "cubic spline" (see Appendix B) is used to determine the root(s) of the characteristic determinant, accuracy of the calculated natural frequency and the mode shape is somewhat sensitive to the choice of the frequency range and the number of frequency points within the frequency range. Experience has shown that a range of 20 percent of the lowest natural frequency should be satisfactory. The number of frequency points should be between four and seven. In many cases, four points are quite adequate. A large number is desirable if two modes are expected to be contained in the designated frequency range. Very little gain in accuracy can be achieved with more than seven points while computation time would be significantly increased. Accuracy of the results can be verified by repeating the calculation with the same number of frequency points along with a smaller frequency range and noting the magnitudes of any changes in the results.

2.3 Representing the Characteristics of the Bearings

Since bearings can influence significantly the dynamics of the rotor, the computer program has been formulated to treat the rotor bearings in a convenient and economical manner. The program first calculates the dynamic characteristics of the rotor using nominal bearings*. This calculation is termed Level I. The program then accepts bearing characteristics that can be anisotropic and that include damping. These characteristics can vary with frequency and with rotor speed. The associated calculations are termed Level II. In effect, in Level II the dynamic properties of the rotor-bearing system are developed from those of Level I for the rotor itself. The economics associated with this technique can be significant, since the Level I calculation is not done repeatedly in an analysis. This technique is, consequently, another feature of the computer program.

In use, the user provides to the program, for each bearing, the value for its nominal stiffness and the values for those actual characteristics which are appropriate in the situation under consideration. For the actual bearing characteristics, each bearing can be characterized at each speed and frequency by as many as 16 quantities. The detailed description of these quantities is given in Section 4.2.4 of this report.

*These nominal bearings are isotropic and contain no damping.

2.4 Producing the Rotordynamics Analyses

Depending on the input setup beyond Level I, the computer program allows the user to produce five different analyses for lateral (bending) vibrations of the rotor-bearing system. Each analysis or run mode is described separately below.

2.4.1 Critical Speeds

Critical speed analysis concerns resonance with mass unbalance. Three restrictive conditions are imposed internally in the computer program when this run mode is selected. Firstly, the excitation frequency is set to be the same as the rotational speed in consistent units. Secondly, anisotropy in the rotor system is ignored. Finally, non-conservative aspects (i.e. damping) in the rotor system are ignored.

Upon finding each critical speed, the normalized mode shape is calculated and printed out. The critical speeds can be determined with the input set up for an idealized rotor model, for which bearing characteristics are assigned as a set of isotropic springs. Since it is desirable to know how the critical speeds vary with bearing stiffness, the calculations can be repeated for new sets of bearing stiffness data with the aid of impedance alteration.

2.4.2 Unbalance Response

To obtain damped unbalance response, the user must provide bearing characteristics at each speed according to the most general format and forcing functions in terms of mass moments. The computer program automatically checks whether or not anisotropy is present then makes allowance for response ellipticity where appropriate. The relative phasing of mass moments among various planes can be assigned by the user. The computer will internally set the forcing function to be of the rotating type regardless of the input entry. Calculated response will be presented as orbit parameters at each of the active stations at speed points specified in the input.

The computer will automatically search for one or more damped critical speed(s) within the specified speed range and compute the corresponding response(s).

2.4.3 Asynchronous Resonances

To determine asynchronous resonances, the user specifies the range of asynchronous frequencies of interest at each rotor speed. He also has the option of specifying bearing support characteristics at each speed-frequency combination. As in the critical speed calculation, non-conservative aspects of the rotor are neglected; however, isotropy is not presumed. The asynchronous resonance mode shapes are calculated along with the natural frequencies. Where isotropy is not preserved, the mode shape is described in terms of orbit parameters.

2.4.4 Asynchronous Response

This run mode is to Asynchronous Resonances as Unbalance Response is to Critical Speeds. There is, however, an additional parameter available to the user to specify the character of the forcing function. Asynchronous excitation may be encountered either in the form of a space fixed system or a rotating system. Gear mesh excitation, partial inlet nozzle, and flow blockage all represent space fixed asynchronous forcing systems. Rotating forcing systems are less common; one example of the latter is an unbalanced rotating stall of a compressor stage. For this reason, the user is allowed to identify whether the forcing function is space fixed or rotating. Again, asynchronous damped resonance is automatically searched within the user-specified frequency range and the response at the corresponding condition is calculated in addition to those at user-specified frequencies.

2.4.4 Stability Analyses

Stability analysis is performed at each user-specified speed by

searching for non-conservative natural modes in user-specified asynchronous frequency ranges. The critical damping ratio is determined along with the natural frequency. A negative critical damping ratio indicates instability. The normalized mode shape of each mode is printed out in terms of orbit parameters at the active stations.

SECTION III

DESCRIPTION OF COMPUTER PROGRAM

This section constitutes a manual for use of the rotordynamics program. It first describes, in detail, the input data and then discusses the output provided by the program. Examples of both input and output are also given.

3.1 Input Data

Input data consist of job title, rotor geometry, material properties, bearing characteristics, dynamic characteristics such as shaft speeds, vibration frequencies and types of excitation, and kinds of dynamic analyses to be performed.

Depending on the particular type of analysis required, the input information may vary. Data cards in sequence and their specifications are listed in the following. Each integer must be right-justified in its field.

In Level I input (Cards 1 - 13)* specify shaft geometry and speed frequency combinations at which subsequent calculations will be carried out. (Cards 2 - 9) specify geometrical, physical and material modelling parameters of the shaft, (Cards 1, 10 - 13) specify the bearings and speed frequency combinations. Card 14 contains control parameters which relate to the type of analysis desired. Cards 15 and 16 deal with additional data (Level II) which, together with structural characterization furnished by Level I input, complete the dynamic specification of the total rotor system. Card 17 allows entry of user-specified conditions to initiate the iterative computations required of a non-conservative rotor system.

*The term "Card" as used for the input data description refers, in general, to a set of input cards. For example, Card 4 is a set of individual cards, one for each shaft segment.

Card 1 -- Number of Speed Groups and Execution Level Control

Column 1 - 5: NCASE, FORMAT (I5) - A positive integer that indicates the number of speed groups to be run for a single set of data (Cards 2 - 9). Cards 10 - 13, 15 - 17 are to be repeated for each speed group to specify further speed-frequency combinations and associated Level II bearing revisions and forcing function designations, within each speed group. If NCASE is set to zero, omit Cards 2 - 13; execution will skip to card 14 using the user-furnished data file on Tape (10), which should contain previously generated Level I interim output. (See KRUN).

Column 6 - 10: KRUN, FORMAT (I5) - Execution level control.

0 - Data (Cards 1 - 13) are stored on Tape (10) for further runs with Level II alterations, execution then stops. (Run Level I only).

1 - Level I data are stored on Tape (10) as above and execution proceeds normally with (Card 14) and any other Level II alterations (Card 15 - 17). (Run Level II).

Card 2 - Title Card

Column 1 - 16: IDENT, FORMAT (4A4) - 15 character job identification code.
Last character in the allowed field
(Column 16) should be a blank for
visual separation from TITLE.

Column 17 - 80: TITLE, FORMAT (16A4) - 64 character job title.

Card 3 - Rotor Model Parameters, Action Stations, and Printout Control (FORMAT (16I5))

Column 1 - 5: ISEG -- Number of shaft segments (maximum 75).

Column 6 - 10: LMAT - Number of different materials of which the rotor is composed.

Column 11 - 15: LMAS - Number of lumped mass stations; e.g., disks, collars and impellers.

Column 16 - 20: LBFA - Number of bearing stations (maximum 4).

Column 21 - 25: LTYP - Type of vibration of the rotor

1	torsion	vibration
2	bending	vibration
3	both	

Column 26 - 30: LEXI - Number of action stations (maximum 20). A geometric station may represent two action stations, see Card 9.

Column 31 - 35: LPRI - Level I bearing printout control.
 0 - default, printout bearing data
 -1 - suppress bearing data output

Card 4 - Geometry of Shaft Segments, FORMAT (I5, 5X, 5F10.0). One Card 4 must be included for each shaft segment; therefore, the value of LSEG on Card 3 equals the number of Card 4's to be included in the input deck.

Column 1 - 5: L -- Shaft segment index number (1 through LSEG).

Column 6 - 10: Blank.

Column 11 - 20: X(L) -- Length of the L-th segment (inches).

Column 21 - 30: D1 -- Stiffness I.D. (inches).

Column 31 - 40: D2 -- Stiffness O.D. (inches).

Column 41 - 50: D3 -- Mass I.D. (inches).

Column 51 - 60: D4 -- Mass O.D. (inches).

NOTE: D3 and D4 cannot be equal.

Card 5 - Material Properties, FORMAT (215, 3E10.4). One card must be provided for each different shaft material; therefore LMAT cards must be provided.

Column 1 - 5: NMAT - Material index number (1 through LMAT).

Column 6 - 10: N - Station number of new material (N must equal 1 on the first Card 5)

Column 11 - 20: DQ - Density (lb./cu.-in.)

Column 21 - 30: E - Young's modulus (lb./sq.-in.)

Column 31 - 40: G - Shear modulus (lb./sq.-in.)

Card 6 -- Physical Properties of Lumped Mass Stations, FORMAT (2I5, 4F10.0)

LMAS cards must be provided (Card 3)

- Column 1 - 5: L - Lumped mass index number (1 through 1MAS).
- Column 6 - 10: N3(L) - Station number of the L-th lumped mass.
- Column 11 - 20: W(L) - Weight of the L-th lumped mass (lb.)
- Column 21 - 30: P(L) - Polar inertia of the L-th lumped mass
(lb.- in.²).
- Column 31 - 40: T(L) - Transverse inertia of the L-th lumped mass
(lb.- in.²).
- Column 41 - 50: Y(L) - Offset of C.G. of the L-th lumped mass,
measured from station N3(L) (inches).

Card 7 - Physical Properties of Bearing Stations, FORMAT (2I5, 6F10.0),
LBEA cards must be provided (Card 3)

- Column 1 - 5: L - Bearing index number (1 through LBEA).
- Column 6 - 10: N5(L) - Station number of the L-th bearing.
- Column 11 - 20: D5(L,1) - Vertical (along x) misalignment of the L-th bearing (inches).
- Column 21 - 30: D5(L,2) - Horizontal (along y) misalignment at the L-th bearing (inches)
- Column 31 - 40: S5(L,1) - Vertical static lineal stiffness of the L-th bearing (lb./in.)
- Column 41 - 50: S5(L,2) - Horizontal static lineal stiffness (lb./in.)
- Column 51 - 60: T5(L,1) - Angular stiffness of the L-th bearing, in the vertical plane (in.-lb./rad.).
- Column 61 - 70: T5(L,2) - Angular stiffness in the horizontal plane (in.-lb./rad.).

The above bearing data are primarily for determining the load distribution among bearings due to gravity and due to bearing misalignment. They are not used for critical speeds or response.

Card 8 - Action Stations, FORMAT (16I5)

Maximum 2 cards (20 stations); LEXI data values must be provided (Card 3). A geometric station may be repeated to designate both lineal and angular actions, see Card 9.

Column 1 - 80: N8(I), I=1 - LEXI - Station number of excitation point.

Since the computer program is based on the distributed analysis of shaft segments, only stations which are important and significant for investigating mode shapes and for assigning mass unbalance or external loads need to be assigned as action stations. Bearing stations, heavy lumped inertia stations, stations with external excitation, and stations where vibration motions are of interest usually fall into this category. The number of action stations should be as small as possible but should include bearings and end stations. Generally 4 to 7 stations are used. If floating number exponent overflow occurs (this often happens on a single precision computer) reduce the number of action stations.

Card 9 - Action Station Capability. FORMAT (16I5)

Maximum 2 cards (20 stations); LEXI data values must be provided (Card 3)

Column 1 - 80: K8(I), I=1-20 LEXI - Excitation type associated with each action station specified on Card 8.

Action station capability characterizes both input and output at the station; e.g., lateral force type denotes force input and/or deflection output. Lateral moment type denotes moment input and/or slope output.

The type of excitation is designated as follows:

<u>K8(I)</u>	<u>Torsional Moment</u>	<u>Lateral Force</u>	<u>Lateral Moment</u>
1	-	-	-
2	X	-	-
3	-	X	-
4	-	-	X
5	X	X	-
6	X	-	X
7	-	X	X
8	X	X	X

Note: Total degrees of freedom must not exceed 40. Each lateral force type or a lateral moment type action station is assigned two degrees of freedom, while each torsional moment type action station is given a single degree of freedom. For example, if $K8(L) = 6$, the L-th action station has a total of $1 + 0 + 2 = 3$ degrees of freedom.

The number of sets of cards 10 - 13 must equal the value of NCASE on Card 1.

Card 10 - Run Mode Control, FORMAT (I5)

Column 1 - 5. LRUN - Synchronism indicator
 ' synchronous frequency
 0 asynchronous frequency

*RUN in card 14 of input must be consistent with the value of LRUN entered here.

Card 11 - Speed Loop Range, FORMAT (2I5, 2F10.0)

For IRUN = 1 or 2 in card 14, LRUN in card 10 must be set to 1, and it is necessary to select a speed range over which analysis is to be conducted and the number of speed points (maximum of 11) of which the range is comprised. A number of speed groups may be used as designated by NCASE in card 1 to cover a large speed range by several speed groups. The speed ranges of various speed groups may overlap or be consecutive or be separated. IFRE would be defaulted internally to a value of 1.

For IRUN = 3, 4, or 5, in card 14, LRUN in card 10 must be set to 0; the rotor speed is constant and therefore the number of speed points is 1 (within each speed group). Under this condition a number of different frequency ranges (other than running) each consisting of a number of frequency points (maximum of 11) may be selected to investigate the asynchronous frequencies. Selection must be made, therefore, of speed groups, speed points (always 1), frequency groups, and frequency points.

Column 1 - 5: I7 - Number of speed points to be run in each speed group.
This determines the number of times the set of cards 12 - 13 are to be repeated as a pair within each speed group (cards 10 - 13).

Column 6 - 10: IFRE - Number of frequency groups at each speed point specified by I7 above (cannot exceed 5).

Column 11 - 20: SPE1 - Lower bound of the speed range.

Column 21 - 30: SPE2 - Upper bound of the speed range.

Card 12 - Nominal Dynamic Bearing Stiffnesses, FORMAT (2I5, 2F10.0),

Total number of cards must equal $LBEA \times I7$.

Column 1 - 5: L - Bearing stations index number (1 through LBEA).

Column 6 - 10: I6 - Input control of dynamic bearing data;

1 continue data entry

0 denotes last data card for current speed group and allows subsequent omission of further repetition of card 12 if bearing data do not vary within a speed group.

Column 11 - 20: XS(L, 1) - Lineal bearing stiffness (lb./in.) for Level I

Column 21 - 30: XS(L, 2) - Angular bearing stiffness (in.-lb./rad.) for Level I only.

The core of computations lies in the speed (outer) and the frequency (inner) loops. The shaft-speed dependent bearing data are entered within the speed loop.

Card 13 - Frequency-Loop Range, FORMAT (2I5, 2F10.0)

Total number of cards must equal $IFRE \times I7$ for each speed group
(card is omitted if $LRUN = 1$).

Column 1 - 5: J - Frequency group index number (1 through $IFRE$).

Column 6 - 10: I8 - Number of frequency points of the frequency loop.

Column 11 - 20: FRQ1 - Lower bound of the frequency range.

Column 21 - 30: FRQ2 - Upper bound of the frequency range.

Card 14 - Run Mode Control Parameters for Level II, FORMAT (1615)

One card for each input setup.

Column 1 - 5: IRUN - Run mode indicator

- 1 compute critical speeds
- 2 determine unbalance response
- 3 compute natural modes of asynchronous resonance
- 4 determine asynchronous response
- 5 perform stability analysis

The allowable value for IRUN must be compatible with the value of LRUN in card 10 as indicated by check marks in the following table.

<u>LRUN</u>	<u>IRUN</u>				
	1	2	3	4	5
0			✓	✓	✓
1	✓	✓			

The program automatically solves the real eigenvalue problem in the specified frequency/speed range for IRUN = 1 and 3. For IRUN = 2, 4 and 5, the complex eigenvalue problem may be treated according to the value assigned to IGEN (column 26 - 30 of this card).

Column 6 - 10: ITYPE - Type of shaft motion due to excitation.

- 0 whirling
- 1 space fixed

(Internally defaulted to 0 for IRUN = 1, 2, 3)

Column 11 - 15: IBRG - Number of bearings to be revised.

The program allows the bearing data used in Level I to be altered. This permits the modelling of anisotropic bearings and bearings having damping, and also permits bearing replacement and the interchange of bearing stations.

Column 16 - 20: IPRI - Controls output of Level II bearing data and excitation force.

0 prints out bearing data and excitation force at each speed point

-1 suppresses printing of bearing data and excitation force

Column 21 - 25: IDIAG - Diagnostic output control

0 no diagnostics

2 complete diagnostics

Column 26 - 30: IGEN - Controls number of damped natural modes to be found in the complex eigenvalue computations.

0 the complex eigenvalue vector subroutine will be bypassed and no complex roots will be sought.

(IRUN = 2, 4, 5)

<0 |IGEN| damped natural modes will be sought and iteration diagnostics will be furnished.

>0 IGEN damped natural modes will be sought without diagnostics output.

Column 31 - 35: ISLO - Controls iteration criterion and speed.

0 yields normal iteration

>0 convergence criterion is multiplied by 10^{ISLO} .

<0 convergence criterion is multiplied by 10^{-ISLO} and iteration stepping for damping is decreased by 2^{ISLO}

Normally set to zero. If iteration oscillates or does not converge, yet a damped natural mode is expected within speed group, try ISLO equal to 1 or -1. Absolute value of ISLO should not exceed 3 and rarely be as high as 2.

Column 36 - 40: IBEG - Allows user input of starting values for complex eigenvalue iterations.

0 use internal logic to determine starting values.
Omit card 17.

-1 read iteration starting values from card 17.

Card 15 - Revision of Bearing Coefficients Control, FORMAT (415)

BRG cards must be provided for each speed frequency combination.

Column 1 - 5: I - Bearing index number (1 through IBEG).

Column 6 - 10: NBRG - Station number of bearing to be revised.

Column 11 - 15: KBRG - New bearing type

1 radial (lineal)

2 angular

Column 16 - 20: IREV - Revision data control

0 use previous data, bypass Card 15A

1 read card 15A

Card 15A - Revision of Bearing Coefficients, FORMAT (8E10.4)

IBRG cards must be provided for each speed-frequency combination (card is omitted if IREV (Card 15) = 0).

Column 1 - 80: KXX, BXX, KXY, BXY, KYX, BYX, KYY, BYY - Bearing coefficients; their identifications are:

First Letter: K, stiffness coefficient

Unit: lb./in. (lineal bearing),

in.-lb./rad. (angular bearings)

B, damping coefficient.

Unit: lb.-sec./in. (lineal bearing)

in.-lb.-sec./rad. (angular bearing)

Second Letter: Reaction coordinate.

Third Letter: Displacement coordinate.

Card 16 - External Excitation Sources, Control FORMAT (2I5)

One card must be provided for each speed-frequency combination (this card and cards 16A, 16B and 16C are omitted if IRUN=1, 3, or 5 on Card 14).

Column 1 - 5: IFORCE - Number of excitation planes excited.

Column 6 - 10: IFDATA - Force data input control
0 use previous data and omit
Cards 16A - 16C.
1 read Cards 16A - 16C.

Cards 16A - 16C - External Excitation Sources

One of each card must be provided for each speed-frequency combination (cards are omitted if IRUN = 1, 3 or 5 or if IFDATA = 0)

Card 16A - FORMAT (16I5)

Column 1 - 80: NFORCE(I), I = 1, IFORCE - Station number of the I-th excited station.

Card 16B - FORMAT (16I5)

Column 1 - 80: KFORCE(I), I = 1, IFORCE - Excitation type
1 lateral force
2 lateral moment

For IRUN = 2 KFORCE must be = 1

For IRUN = 4 KFORCE may be 1 or 2

Card 16C - FORMAT (4E10.4)

Column 1 - 40: F1, G1, F2, G2 - Excitation components
First letter = F component in-phase with time reference
G component leading time reference by 90 degrees
Second letter = 1 forward rotation (whirl) (ITYPE = 0; i.e., rotating excitation)
2 backward rotation (whirl)
(backward rotation would be applicable to counter rotating shafts)

Card 17 - User Furnished Starting Values for Complex Eigenvalue Iterations.

FORMAT (2E20.4)

These cards are required if IBEG (card 14) = -1 and if IGEN
(card 14) $\neq$ 0. |IGEN| cards must be supplied for each iteration
set. An iteration set is a speed group for IRUN = 2 or a
frequency group for IRUN = 4 or 5.

Column 1 - 10: FBRG - Iteration starting frequency.

Unit: Hz

CBRG - Iteration starting damping coefficient.

Unit: lb.-sec./in.

3.2 Input Samples

The input samples are based on a model rotor which was previously analyzed and tested by Tonnesen and Lund [15]. The model rotor is 46.85 inch (1190 mm) long and its total weight is 413.32 lbs. The shaft is divided into 32 segments with 18 inertial stations and 2 bearing stations. A scaled outline of the model rotor is shown in Figure 2. In the dynamic analysis, 4 action stations are chosen; they include 2 bearing stations and 2 inertia stations.

The original rotor is supported by two identical fluid-film bearings of the plain journal type. Each bearing has a radial clearance of 0.00181 inch, a bore diameter of 2.468 inch and a length of 0.74 inch. The pedestal supports are considered to be rigid. The dimensionless dynamic coefficients of this bearing have been kindly furnished by Prof. Lund and are listed in Table 3. Fluid viscosity of 3.349 cp is used in the sample calculations.

The present section will describe the setup of the input cards for solving various rotor dynamics problems. Emphasis here will be placed on illustrating the contents of the setups. In some studies, it is necessary to run the program several times. The input data of the next run will necessarily depend on the results of the previous run. Thus, in order to give the rationale for selecting the particular content of input data, occasional reference will be made to relevant portions of output data which is to be presented later in Section 3.4.

3.2.1 Critical Speeds (IRUN = 1)

As ball bearings are commonly used in many rotor systems, the critical speed calculation will be illustrated with the original fluid-film bearings replaced by a pair of deep-groove ball bearings. The stiffness coefficients were computed by a separate computer program prepared for the USAF under the same contract [16].

A complete set of input cards for the determination of a critical speed of the ball bearing rotor is shown in Table 4. Due to preload,

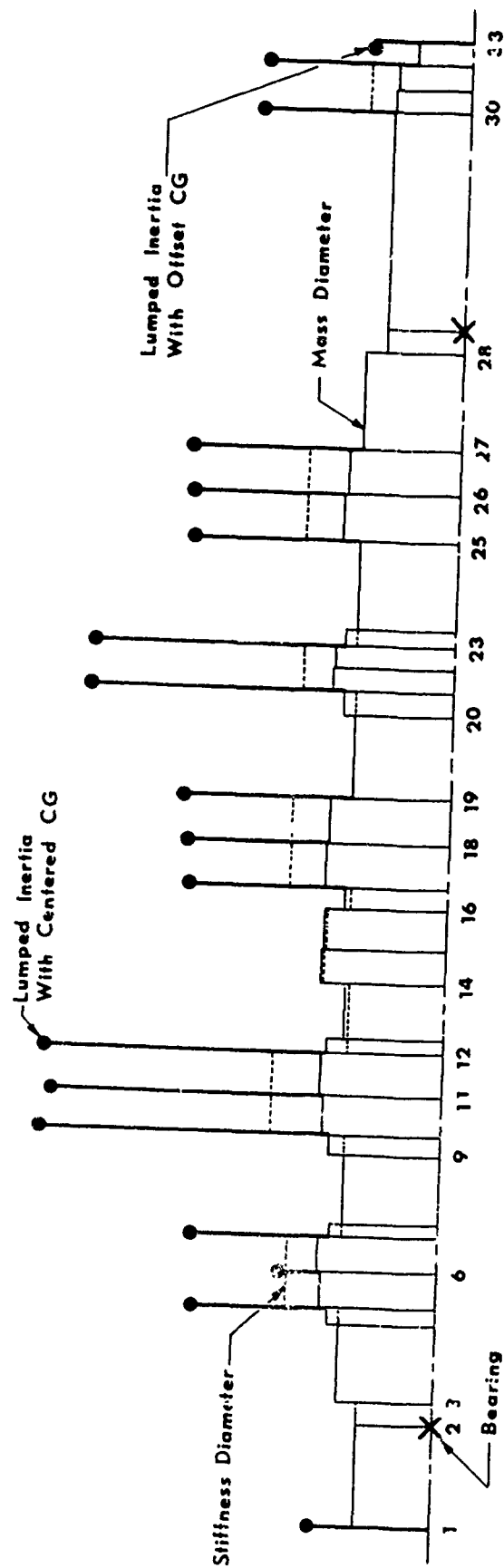


Figure 2 Outline of Sample Rotor

TABLE 1
DIMENSIONLESS DYNAMIC COEFFICIENTS OF JOURNAL BEARING
USED IN SAMPLE ANALYSIS

BEARING TYPE: PLAIN CYLINDRICAL JOURNAL ($L/D = 0.3$)
(Courtesy of Prof. J. W. Lund)

1/S	C_{xx}/W	C_{yy}/W	C_{xy}/W	C_{yx}/W	$\epsilon C_{xx}/\%$	$\epsilon C_{yy}/\%$	$\epsilon C_{xy}/W$	$\epsilon C_{yx}/W$
3.97100D-01	2.11750D 00	1.99290D 00	4.15120D 00	-1.53160D 00	7.76580D 00	3.73570D 00	2.13760D 00	2.13760D 00
4.51500D-01	2.25070D 00	1.96480D 00	4.02760D 00	-1.34910D 00	7.47140D 00	3.41220D 00	2.10520D 00	2.10520D 00
5.74800D-01	2.53300D 00	1.91680D 00	3.87730D 00	-1.03330D 00	7.08110D 00	2.91310D 00	2.05150D 00	2.05150D 00
7.21400D-01	2.84270D 00	1.87840D 00	3.81210D 00	-7.91800D-01	6.86570D 00	2.54260D 00	2.01100D 00	2.01100D 00
9.00400D-01	3.19160D 00	1.84320D 00	3.80070D 00	-5.86700D-01	6.76130D 00	2.24490D 00	1.97360D 00	1.97360D 00
1.12370D 00	3.58920D 00	1.81160D 00	3.83120D 00	-4.06100D-01	6.74200D 00	1.99900D 00	1.94100D 00	1.94100D 00
1.49860D 00	4.04930D 00	1.78290D 00	3.89720D 00	-2.41300D-01	6.79380D 00	1.78990D 00	1.91230D 00	1.91230D 00
1.78030D 00	4.59080D 00	1.75670D 00	3.99950D 00	-8.58000D-02	6.91130D 00	1.60890D 00	1.88710D 00	1.88710D 00
2.27830D 00	5.24090D 00	1.73290D 00	4.13070D 00	6.57000D-02	7.09590D 00	1.44640D 00	1.86500D 00	1.86500D 00
2.96820D 00	6.03880D 00	1.71100D 00	4.30430D 00	2.18100D-01	7.35550D 00	1.30040D 00	1.84600D 00	1.84600D 00
3.22680D 00	6.31540D 00	1.70490D 00	4.36510D 00	2.64800D-01	7.44980D 00	1.25900D 00	1.84090D 00	1.84090D 00
3.72860D 00	6.82400D 00	1.69510D 00	4.47700D 00	3.44500D-01	7.62690D 00	1.19220D 00	1.83310D 00	1.83310D 00
5.44960D 00	8.36460D 00	1.67370D 00	4.81070D 00	5.50200D-01	8.17230D 00	1.04050D 00	1.81800D 00	1.81800D 00
1.20330D 01	1.28286D 01	1.64580D 00	5.69510D 00	9.92400D-01	6.68620D 00	8.01700D-01	1.80340D 00	1.80340D 00
4.13220D 01	2.54861D 01	1.63109D 00	7.67880D 00	1.84810D 00	1.31878D 01	5.49100D-01	1.79840D 00	1.79840D 00

Nomenclature: S Sommerfeld Number
C Radial Bearing Clearance
 K_{xx} , K_{yy} , etc. Stiffness Coefficients
 C_{xx} , C_{yy} , etc. Damping Coefficients
 B_{xx} , B_{yy} , etc. Shaft Rotational Speed (radians/sec.)

TABLE 4

EXAMPLE OF INPUT DATA FOR CRITICAL SPEED ANALYSIS

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80	81	82	83	84	85	86	87	88	89	90	91	92	93	94	95	96	97	98	99	100	101	102	103	104	105	106	107	108	109	110	111	112	113	114	115	116	117	118	119	120	121	122	123	124	125	126	127	128	129	130	131	132	133	134	135	136	137	138	139	140	141	142	143	144	145	146	147	148	149	150	151	152	153	154	155	156	157	158	159	160	161	162	163	164	165	166	167	168	169	170	171	172	173	174	175	176	177	178	179	180	181	182	183	184	185	186	187	188	189	190	191	192	193	194	195	196	197	198	199	200	201	202	203	204	205	206	207	208	209	210	211	212	213	214	215	216	217	218	219	220	221	222	223	224	225	226	227	228	229	230	231	232	233	234	235	236	237	238	239	240	241	242	243	244	245	246	247	248	249	250	251	252	253	254	255	256	257	258	259	260	261	262	263	264	265	266	267	268	269	270	271	272	273	274	275	276	277	278	279	280	281	282	283	284	285	286	287	288	289	290	291	292	293	294	295	296	297	298	299	300	301	302	303	304	305	306	307	308	309	310	311	312	313	314	315	316	317	318	319	320	321	322	323	324	325	326	327	328	329	330	331	332	333	334	335	336	337	338	339	340	341	342	343	344	345	346	347	348	349	350	351	352	353	354	355	356	357	358	359	360	361	362	363	364	365	366	367	368	369	370	371	372	373	374	375	376	377	378	379	380	381	382	383	384	385	386	387	388	389	390	391	392	393	394	395	396	397	398	399	400	401	402	403	404	405	406	407	408	409	410	411	412	413	414	415	416	417	418	419	420	421	422	423	424	425	426	427	428	429	430	431	432	433	434	435	436	437	438	439	440	441	442	443	444	445	446	447	448	449	450	451	452	453	454	455	456	457	458	459	460	461	462	463	464	465	466	467	468	469	470	471	472	473	474	475	476	477	478	479	480	481	482	483	484	485	486	487	488	489	490	491	492	493	494	495	496	497	498	499	500	501	502	503	504	505	506	507	508	509	510	511	512	513	514	515	516	517	518	519	520	521	522	523	524	525	526	527	528	529	530	531	532	533	534	535	536	537	538	539	540	541	542	543	544	545	546	547	548	549	550	551	552	553	554	555	556	557	558	559	560	561	562	563	564	565	566	567	568	569	570	571	572	573	574	575	576	577	578	579	580	581	582	583	584	585	586	587	588	589	590	591	592	593	594	595	596	597	598	599	600	601	602	603	604	605	606	607	608	609	610	611	612	613	614	615	616	617	618	619	620	621	622	623	624	625	626	627	628	629	630	631	632	633	634	635	636	637	638	639	640	641	642	643	644	645	646	647	648	649	650	651	652	653	654	655	656	657	658	659	660	661	662	663	664	665	666	667	668	669	670	671	672	673	674	675	676	677	678	679	680	681	682	683	684	685	686	687	688	689	690	691	692	693	694	695	696	697	698	699	700	701	702	703	704	705	706	707	708	709	710	711	712	713	714	715	716	717	718	719	720	721	722	723	724	725	726	727	728	729	730	731	732	733	734	735	736	737	738	739	740	741	742	743	744	745	746	747	748	749	750	751	752	753	754	755	756	757	758	759	760	761	762	763	764	765	766	767	768	769	770	771	772	773	774	775	776	777	778	779	780	781	782	783	784	785	786	787	788	789	790	791	792	793	794	795	796	797	798	799	800	801	802	803	804	805	806	807	808	809	810	811	812	813	814	815	816	817	818	819	820	821	822	823	824	825	826	827	828	829	830	831	832	833	834	835	836	837	838	839	840	841	842	843	844	845	846	847	848	849	850	851	852	853	854	855	856	857	858	859	860	861	862	863	864	865	866	867	868	869	870	871	872	873	874	875	876	877	878	879	880	881	882	883	884	885	886	887	888	889	890	891	892	893	894	895	896	897	898	899	900	901	902	903	904	905	906	907	908	909	910	911	912	913	914	915	916	917	918	919	920	921	922	923	924	925	926	927	928	929	930	931	932	933	934	935	936	937	938	939	940	941	942	943	944	945	946	947	948	949	950	951	952	953	954	955	956	957	958	959	960	961	962	963	964	965	966	967	968	969	970	971	972	973	974	975	976	977	978	979	980	981	982	983	984	985	986	987	988	989	990	991	992	993	994	995	996	997	998	999	1000	1001	1002	1003	1004	1005	1006	1007	1008	1009	1010	1011	1012	1013	1014	1015	1016	1017	1018	1019	1020	1021	1022	1023	1024	1025	1026	1027	1028	1029	1030	1031	1032	1033	1034	1035	1036	1037	1038	1039	1040	1041	1042	1043	1044	1045	1046	1047	1048	1049	1050	1051	1052	1053	1054	1055	1056	1057	1058	1059	1060	1061	1062	1063	1064	1065	1066	1067	1068	1069	1070	1071	1072	1073	1074	1075	1076	1077	1078	1079	1080	1081	1082	1083	1084	1085	1086	1087	1088	1089	1090	1091	1092	1093	1094	1095	1096	1097	1098	1099	1100	1101	1102	1103	1104	1105	1106	1107	1108	1109	1110	1111	1112	1113	1114	1115	1116	1117	1118	1119	1120	1121	1122	1123	1124	1125	1126	1127	1128	1129	1130	1131	1132	1133	1134	1135	1136	1137	1138	1139	1140	1141	1142	1143	1144	1145	1146	1147	1148	1149	1150	1151	1152	1153	1154	1155	1156	1157	1158	1159	1160	1161	1162	1163	1164	1165	1166	1167	1168	1169	1170	1171	1172	1173	1174	1175	1176	1177	1178	1179	1180	1181	1182	1183	1184	1185	1186	1187	1188	1189	1190	1191	1192	1193	1194	1195	1196	1197	1198	1199	1200	1201	1202	1203	1204	1205	1206	1207	1208	1209	1210	1211	1212	1213	1214	1215	1216	1217	1218	1219	1220	1221	1222	1223	1224	1225	1226	1227	1228	1229	1230	1231	1232	1233	1234	1235	1236	1237	1238	1239	1240	1241	1242	1243	1244	1245	1246	1247	1248	1249	1250	1251	1252	1253	1254	1255	1256	1257	1258	1259	1260	1261	1262	1263	1264	1265	1266	1267	1268	1269	1270	1271	1272	1273	1274	1275	1276	1277	1278	1279	1280	1281	1282	1283	1284	1285	1286	1287	1288	1289	1290	1291	1292	1293	1294	1295	1296	1297	1298	1299	1300	1301	1302	1303	1304	1305	1306	1307	1308	1309	1310	1311	1312	1313	1314	1315	1316	1317	1318	1319	1320	1321	1322	1323	1324	1325	1326	1327	1328	1329	1330	1331	1332	1333	1334	1335	1336	1337	1338	1339	1340	1341	1342	1343	1344	1345	1346	1347	1348	1349	1350	1351	1352	1353	1354	1355	1356	1357	1358	1359	1360	1361	1362	1363	1364	1365	1366	1367	1368	1369	1370	1371	1372	1373	1374	1375	1376	1377	1378	1379	1380	1381	1382	1383	1384	1385	1386	1387	1388	1389	1390	1391	1392	1393	1394	1395	1396	1397	1398	1399	1400	1401	1402	1403	1404	1405	1406	1407	1408	1409	1410	1411	1412	1413	1414	1415	1416	1417	1418	1419	1420	1421	1422	1423	1424	1425	1426	1427	1428	1429	1430	1431	1432	1433	1434	1435	1436	1437	1438	1439	1440	1441	1442	1443	1444	1445	1446	1447	1448	1449	1450	1451	1452	1453	1454	1455	1456	1457	1458	1459	1460	1461	1462	1463	1464	1465	1466	1467	1468	1469	1470	1471	1472	1473	1474	1475	1476	1477	1478	1479	1480	1481	1482	1483	1484	1485	1486	1487	1

the ball bearing is essentially isotropic. Damping is usually negligible. Body forces on the rolling elements alter the contact compliance between each rolling element and the races, therefore the stiffness of the ball bearing is somewhat speed dependent. Thus a ball bearing support can be modelled as an isotropic spring with a speed dependent stiffness and can be completely specified at Level 1 (card 12). Subsequently, at Level 2, it is not necessary to revise dynamic bearing data (IBRG = 0 in card 14). It may also be noted that the static bearing stiffness values are left as zero because they are used only to calculate the bearing load distribution, which is independent of the stiffness values in a two bearing rotor system.

3.2.2 Unbalance Response (IRUN = 2)

To allow safe operation above one or more critical speeds, a popular trend is to damp-mount a ball bearing rotor. A damper, in parallel with a centering spring, is installed around the outer race of the ball bearing. The centering spring should be soft enough to allow the damper to function effectively; at the same time it should be stiff enough to limit eccentricity of the rotor from becoming excessive. The unbalance response analysis will illustrate the use of damp mounting of the ball bearing rotor considered above. The stiffness of the centering spring is chosen to be about $1/4$ of that of the ball bearing. For the present purpose, 800,000 lb./in. and 200,000 lb./in. are respectively assumed to be the stiffness values of each ball bearing and of each centering spring.

Before proceeding to calculate unbalance response of the damp-mounted rotor, it is first necessary to determine the critical speeds of the soft-mounted rotor. A Level I analysis is performed for this purpose. Ground-to-rotor stiffness value at each support point is 160,000 lb./in., which is arrived at by adding the compliance values (reciprocals of the stiffness values) of the ball bearing and of the centering spring to get the overall compliance. The input set-up for the Level I analysis of the soft-mounted rotor

is given in Table 5. Those portions of this input deck which are the same as those in Table 4 are omitted to save space. A single speed range of 2000-9000 rpm is used for this study.

An examination of locations of sign reversals of "co-rotational end determinants," which have been determined by the Level I analysis, revealed critical speeds to be near 4350 rpm and 7000 rpm. Unbalance response analysis is therefore set up for two speed ranges; namely 4000-5000 rpm and 6000-8000 rpm. The damper is assumed to be the viscous type and its damping coefficient is assumed to render a rigid rotor critical damping ratio of 0.2 at 4500 rpm. The effective values of ground-to-rotor stiffness and damping coefficient should both be speed dependent according to Section 4.2.4. The degree of speed dependence of the effective stiffness coefficient turns out to be quite small; that of the effective damping coefficient is somewhat more significant but can still be neglected within each speed range. Therefore, the dynamic bearing data for Level II calculation is given a constant isotropic stiffness coefficient and a constant isotropic damping coefficient in each of the two speed ranges. Such an input set-up is given in Table 6; again, only those data lines different from those in the previous examples are shown. A single unit unbalance (1 in.-oz.) is assigned to a different axial location in order to maximize the relevant modal response in each speed range. By setting NCASE = 2 in card 1, a single input set-up is used to study both speed ranges.

3.2.3 Asynchronous Resonance (IRUN = 3)

The asynchronous resonance analysis is quite similar to the critical speed analysis. However, the (asynchronous) resonance condition is searched through for a frequency range at constant shaft speed. Also, backward whirls and/or anisotropy can be considered. A Level I example, as shown in Table 7, will demonstrate the possibility of incorporating the approximate behavior of the fluid film bearing at non-synchronous conditions and an estimation of the torsional resonance frequency of the rotor. In card 1, NCASE is set to 2, even though in both speed groups rotor speed is 8000 rpm. This is done so that the dynamic bearing stiffness

TABLE 5

EXAMPLE OF INPUT DATA FOR LEVEL 1 ANALYSIS

1	2	3	4	5	6	7	Card Number	Remarks
1234567890	1234567890	1234567890	1234567890	1234567890	1234567890	1234567890	1	Level 1 Only
1	0						2	
TEST IRUN=24	LUND	ROTOR UNBALANCE RESPONSE WITH	SOFT-MOUNTED DAMPER				3	
32	1 18 2	2 4	0				4-7	Same as Table 4
							8	
2 11	18 29						9	
3 3	3 3						10	Synchronous
1							11	
11 1	2000.0	9000.0					12	2 Bearing Set
1 1	160000.0	0.0						Use for All Speeds
2 0	160000.0	0.0						
1	2	3	4	5	6	7		
1234567890	1234567890	1234567890	1234567890	1234567890	1234567890	1234567890		

EXAMPLE OF INPUT DATA FOR DAMPED UNBALANCED RESPONSE

1	2	3	4	5	6	7	Card Number	Remarks	
23456789	1234567890	1234567890	1234567890	124567890	1234567890	1234567890	1	2 Speed Groups	
TEST IRUN=3H LUN= ROTOR UNBALANCE RESPONSE WITH SOFT-MOUNTED DAMPER							2		
32	1	18	2	2	4	0	3		
							4-7	Same as Table 4	
2	11	18	29				8		
3	3	3	3				9		
1							10	Speed Group No. 1	
2	1	4000.0	5000.0				11	9 Speed Points	
1	1	160000.0	0.0				12		
2	0	160000.0	0.0				10	Speed Group No. 2	
1							11	9 Speed Points	
2	1	6000.0	8000.0				12		
1	1	160000.0	0.0				14	2 Level If Brgs.	
2	0	160000.0	0.0				15	Speed Group No. 1	
1	2	0	0	0	0	0	15A		
1.5282D+05	1.0056D+02	0.0	0.0	0.0	0.0	1.5282D+05	1.0056D+02	15	
2	29	1	1				15A		
1.5282D+05	1.0056D+02	0.0	0.0	0.0	0.0	1.5282D+05	1.0056D+02	16	
1	1							16A	
18							16B		
1							16C		
1.0	0.0	0.0	0.0				15	Bearing Default	
1	2	1	0				16	Excit'n Default	
2	29	1	0				15	Bearing Default	
1	0							16	Excit'n Default
1	2	1	0				15	Bearing Default	
2	29	1	0				16	Excit'n Default	
1	0							15	Bearing Default
1	2	1	0				16	Excit'n Default	
2	29	1	0				15	Bearing Default	
1	0							16	Excit'n Default
1	2	1	0				15	Bearing Default	
2	29	1	0				16	Excit'n Default	
1	0							15	Bearing Default
1	2	1	0				16	Excit'n Default	
2	29	1	0				15	Bearing Default	
1	0							16	Excit'n Default
1	2	1	0				15	Bearing Default	
2	29	1	0				16	Excit'n Default	
1.4545D+05	9.1544D+01	0.0	0.0	0.0	0.0	1.4545D+05	9.1544D+02	15	Speed Group No. 2
2	29	1	1				15A		
1.4545D+05	9.1544D+01	0.0	0.0	0.0	0.0	1.4545D+05	9.1544D+02	16	
1							16A		
22							16B		
1							16C		
1.0	0.0	0.0	0.0				15	Bearing Default	
1	2	1	0				16	Excit'n Default	
2	29	1	0				15	Bearing Default	
1	0							16	Excit'n Default
1	2	1	0				15	Bearing Default	
2	29	1	0				16	Excit'n Default	
1	0							15	Bearing Default
1	2	1	0				16	Excit'n Default	
2	29	1	0				15	Bearing Default	
1	0							16	Excit'n Default
1	2	1	0				15	Bearing Default	
2	29	1	0				16	Excit'n Default	
1	0							15	Bearing Default
1	2	1	0				16	Excit'n Default	
2	29	1	0				15	Bearing Default	
1	0							16	Excit'n Default
1	2	1	0				15	Bearing Default	
2	29	1	0				16	Excit'n Default	
1	0							15	Bearing Default
1	2	1	0				16	Excit'n Default	
2	29	1	0				15	Bearing Default	
1	0							16	Excit'n Default
1	2	1	0				15	Bearing Default	
2	29	1	0				16	Excit'n Default	
1	0							15	Bearing Default
1	2	1	0				16	Excit'n Default	
2	29	1	0				15	Bearing Default	
1	0							16	Excit'n Default
1	2	1	0				15	Bearing Default	
2	29	1	0				16	Excit'n Default	
1	0							15	Bearing Default
1	2	1	0				16	Excit'n Default	
2	29	1	0				15	Bearing Default	
1	0							16	Excit'n Default
1	2	1	0				15	Bearing Default	
2	29	1	0				16	Excit'n Default	
1	0							15	Bearing Default
1	2	1	0				16	Excit'n Default	
2	29	1	0				15	Bearing Default	
1	0							16	Excit'n Default
1	2	1	0				15	Bearing Default	
2	29	1	0				16	Excit'n Default	
1	0							15	Bearing Default
1	2	1	0				16	Excit'n Default	
2	29	1	0				15	Bearing Default	
1	0							16	Excit'n Default
1	2	1	0				15	Bearing Default	
2	29	1	0				16	Excit'n Default	
1	0							15	Bearing Default
1	2	1	0				16	Excit'n Default	
2	29	1	0				15	Bearing Default	
1	0							16	Excit'n Default
1	2	1	0				15	Bearing Default	
2	29	1	0				16	Excit'n Default	
1	0							15	Bearing Default
1	2	1	0				16	Excit'n Default	
2	29	1	0				15	Bearing Default	
1	0							16	Excit'n Default
1	2	1	0				15	Bearing Default	
2	29	1	0				16	Excit'n Default	
1	0							15	Bearing Default
1	2	1	0				16	Excit'n Default	
2	29	1	0				15	Bearing Default	
1	0							16	Excit'n Default
1	2	1	0				15	Bearing Default	
2	29	1	0				16	Excit'n Default	
1	0							15	Bearing Default
1	2	1	0				16	Excit'n Default	
2	29	1	0				15	Bearing Default	
1	0							16	Excit'n Default
1	2	1	0				15	Bearing Default	
2	29	1	0				16	Excit'n Default	
1	0							15	Bearing Default
1	2	1	0				16	Excit'n Default	
2	29	1	0				15	Bearing Default	
1	0							16	Excit'n Default
1	2	1	0				15	Bearing Default	
2	29	1	0				16	Excit'n Default	
1	0							15	Bearing Default
1	2	1	0				16	Excit'n Default	
2	29	1	0				15	Bearing Default	
1	0							16	Excit'n Default
1	2	1	0				15	Bearing Default	
2	29	1	0				16	Excit'n Default	
1	0							15	Bearing Default
1	2	1	0				16	Excit'n Default	
2	29	1	0				15	Bearing Default	
1	0							16	Excit'n Default
1	2	1	0				15	Bearing Default	
2	29	1	0				16	Excit'n Default	
1	0							15	Bearing Default
1	2	1	0				16	Excit'n Default	
2	29	1	0				15	Bearing Default	
1	0							16	Excit'n Default
1	2	1	0				15	Bearing Default	
2	29	1	0				16	Excit'n Default	
1	0							15	Bearing Default
1	2	1	0				16	Excit'n Default	
2	29	1	0				15	Bearing Default	
1	0							16	Excit'n Default
1	2	1	0				15	Bearing Default	
2	29	1	0				16	Excit'n Default	
1	0							15	Bearing Default
1	2	1	0				16	Excit'n Default	
2	29	1	0				15	Bearing Default	
1	0							16	Excit'n Default
1	2	1	0				15	Bearing Default	
2	29	1	0				16	Excit'n Default	
1	0							15	Bearing Default
1	2	1	0				16	Excit'n Default	
2	29	1	0				15	Bearing Default	
1	0							16	Excit'n Default
1	2	1	0				15	Bearing Default	
2	29	1	0				16	Excit'n Default	
1	0							15	Bearing Default
1	2	1	0				16	Excit'n Default	
2	29	1	0				15	Bearing Default	
1	0							16	Excit'n Default
1	2	1	0				15	Bearing Default	
2	29	1	0				16	Excit'n Default	
1	0							15	Bearing Default
1	2	1	0				16	Excit'n Default	
2	29	1	0				15	Bearing Default	
1	0							16	Excit'n Default
1	2	1	0				15	Bearing Default	
2	29	1	0				16	Excit'n Default	
1	0							15	Bearing Default
1	2	1	0				16	Excit'n Default	
2	29	1	0				15	Bearing Default	
1	0							16	Excit'n Default
1	2	1	0				15	Bearing Default	
2	29	1	0				16	Excit'n Default	
1	0							15	Bearing Default
1	2	1	0				16	Excit'n Default	
2	29	1	0				15	Bearing Default	
1	0							16	Excit'n Default
1	2	1	0				15	Bearing Default	
2	29	1	0				16	Excit'n Default	
1	0							15	Bearing Default
1	2	1	0				16	Excit'n Default	
2	29	1	0				15	Bearing Default	
1	0							16	Excit'n Default
1	2	1	0				15	Bearing Default	
2	29	1	0				16	Excit'n Default	
1	0							15	Bearing Default
1	2	1	0				16	Excit'n Default	
2	29	1	0				15	Bearing Default	
1	0							16	Excit'n Default
1	2	1	0				15	Bearing Default	
2	29	1	0				16	Excit'n Default	
1	0							15	Bearing Default
1	2	1	0				16	Excit'n Default	
2	29	1	0				15	Bearing Default	
1	0							16	Excit'n Default
1	2	1	0				15	Bearing Default	
2	29	1	0				16	Excit'n Default	
1	0							15	Bearing Default
1	2	1	0				16	Excit'n Default	
2	29	1	0				15	Bearing Default	
1	0							16	Excit'n Default
1	2	1	0				15	Bearing Default	
2	29	1	0				16	Excit'n Default	
1	0							15	Bearing Default
1	2	1	0				16	Excit'n Default	
2	29	1	0				15	Bearing Default	
1	0							16	Excit'n Default
1	2	1	0				15	Bearing Default	
2	29	1	0				16	Excit'n Default	
1	0							15	Bearing Default
1	2	1	0				16	Excit'n Default	
2	29	1	0				15	Bearing Default	
1	0							16	Excit'n Default
1	2	1	0				15	Bearing Default	
2	29	1	0				16	Excit'n Default	
1	0							15	Bearing Default
1	2	1	0				16	Excit'n Default	
2	29	1	0				15	Bearing Default	
1	0							16	Excit'n Default
1	2	1	0				15	Bearing Default	
2	29	1	0				16	Excit'n Default	
1	0							15	Bearing Default
1	2	1	0				16	Excit'n Default	
2	29	1	0				15	Bearing Default	
1	0							16	Excit'n Default
1	2	1	0				15	Bearing Default	
2	29	1	0				16	Excit'n Default	
1	0							15	Bearing Default
1	2	1	0				16	Excit'n Default	
2	29	1	0				15	Bearing Default	
1	0							16	Excit'n Default
1	2	1	0				15	Bearing Default	
2	29	1	0				16	Excit'n Default	
1	0							15	Bearing Default
1	2	1	0				16	Excit'n Default	
2	29	1	0				15	Bearing Default	
1	0							16	Excit'n Default
1	2	1	0				15	Bearing Default	
2	29	1	0				16	Excit'n Default	
1	0							15	Bearing Default
1	2	1	0				16	Excit'n Default	
2	29	1	0				15	Bearing Default	
1	0							16	Excit'n Default

TABLE 7

EXAMPLE OF INPUT DATA FOR ASYNCHRONOUS BENDING AND TORSIONAL RESONANCE STUDIES

12345678901	1	2345678901	2	2345678901	3	2345678901	4	2345678901	5	2345678901	6	2345678901	7	2345678901	Card Number	Remarks
TEST IRUN=3A	0	18	2	2	3	4	0								1	Level 1 Only
32	1	18	2	2	3	4	0								2	Torsion & Bending
															3	Same As Table 4
															4-7	
															8	
															9	
															10	Speed Group #1 (Asynch)
															11	1 Freq. Group
															12	
															13	7 Freq. Points
															10	Speed Group #2
															11	2 Freq. Groups
															12	
															13	Freq. Group #1, 9 Points
															13	Freq. Group #2, 5 Points
12345678901	1	2345678901	2	2345678901	3	2345678901	4	2345678901	5	2345678901	6	2345678901	7	2345678901	Card Number	Remarks
															1	Level 1 Only
															2	Torsion & Bending
															3	Same As Table 4
															4-7	
															8	
															9	
															10	Speed Group #1 (Asynch)
															11	1 Freq. Group
															12	
															13	7 Freq. Points
															10	Speed Group #2
															11	2 Freq. Groups
															12	
															13	Freq. Group #1, 9 Points
															13	Freq. Group #2, 5 Points

values can be varied according to the center frequency of each frequency range. The approximate non-synchronous stiffness value of the fluid film bearing is determined by a procedure described in a separate report of the present contract [17]. LTYP = 3 in card 3 designates that both bending and torsional analyses are to be performed. The first speed group contains a frequency range to explore the "rigid mode" with a reduced stiffness value which corresponds to the "half speed" behavior of a fluid film bearing. The second speed group contains two frequency ranges; the first of these concerns the relatively stiff near-synchronous behavior of the fluid film bearing, and the second frequency range is intended to locate the torsional resonance frequency.

Bending asynchronous behavior of the rotor is further studied by invoking Level II calculations to establish asynchronous resonance frequencies and the associated mode shapes. LTYP is changed to 2 in card 3 to dedicate the study to bending motions exclusively. The second frequency range in the second speed group is accordingly removed. Because the isotropy approximation is retained, it is not necessary to introduce new dynamic bearing data in Level II. Table 8 shows the input data for calculating asynchronous bending resonances.

3.2.4 Asynchronous Response (IRUN = 4)

Damped asynchronous response is considered with fluid-film bearing data derived from Table 3. Dimensions and lubricant properties are indicated in the beginning of Section 3.2. Load levels of each bearing are based on Level I calculation (see Item 5.0 in Table 13).

This calculation is performed with the same speed-frequency combinations used in the previous analysis (Table 8), which has generated an intermediate data file that is reusable. Therefore, the present calculation begins with Level II by accessing the pre-stored intermediate data file (NCASE = 0 in card 1). Table 9 contains the complete input set-up for this run.

TABLE 8
EXAMPLE OF INPUT DATA FOR ASYNCHRONOUS BENDING RESONANCES

1	2	3	4	5	6	7	Card Number	Remarks
1234567890	1234567890	1234567890	1234567890	1234567890	1234567890	1234567890	1	Both Levels
2							2	
32	1	18	2	4	0		3	
TEST IRUN=3,4,5 LUND ROTOR ASYNCHRONOUS BENDING ANALYSIS								
							4-7	Same as Table 4
2	11	18	29				8	
3	3	3	3				9	
0							10	Freq. Group No. 1
1	1	8000.0	8000.0				11	
1	1	129500.0	0.0				12	
2	0	153500.0	0.0				13	
1	7	63.0	73.5				10	Freq. Group No. 2
0							11	
1	1	8000.0	8000.0				12	
1	1	984400.0	0.0				13	
2	0	1272000.0	0.0				14	
1	9	92.8	113.1					
3	1	0	0	0	0			
1234567890	1234567890	1234567890	1234567890	1234567890	1234567890	1234567890	5	
							6	
							7	

TABLE 9

EXAMPLE OF INPUT DATA FOR DAMPED ASYNCHRONOUS RESPONSE
TWO NATURAL MODES SOUGHT WITH USER-SPECIFIED TRIAL CONDITIONS

1	2	3	4	5	6	7	Card Number	Remarks
12345678901	2345678901	2345678901	2345678901	2345678901	2345678901	2345678901	1	Level II Only
0							14	2 M.Iter. Supply SV
4	1	2	0	0	-2	0	15	Freq.Gr.1; 7 Freq Pts
1	2	1	1				15A	Data-Bearing
6.6956E+05	7.2412E+02	4.5395E+05	2.2607E+02	3.0312E+04	2.2607E+02	1.7531E+05	15	
2	29	1	1				15A	Data-Bearing No. 2
8.9993E+05	1.1572E+03	5.6968E+05	2.7264E+02	4.9946E+04	2.7264E+02	2.1097E+05	16	
1	1						16A	
18							16B	Ex. at St. No. 18
1							16C	
1.0	0.0	0.0	0.0				15	6 Sets - Data Default
1	2	1	0				16	
2	29	1	0				15	
1	0						16	
1	2	1	0				15	
2	29	1	0				16	
1	0						15	
1	2	1	0				16	
2	29	1	0				15	
1	0						16	
1	2	1	0				15	
2	29	1	0				16	
1	0						15	
1	2	1	0				16	
2	29	1	0				15	
1	0						16	
6.8114D+01		1.3569D-00					17	SV Mode No. 1 (Conv.)
6.8114D+01		1.3569D-00					15	SV Mode No. 2 (Repeat)
1	2	1	1				15A	Freq.Gr.2; 9 Freq.Pts
6.6956E+05	7.2412E+02	4.5395E+05	2.2607E+02	3.0312E+04	2.2607E+02	1.7531E+05	15	
2	29	1	1				15A	
8.9993E+05	1.1572E+03	5.6968E+05	2.7264E+02	4.9946E+04	2.7264E+02	2.1097E+05	16	
1	1						16A	
29							16B	Ex. at St. #29
1							16C	
1.0	0.0	0.0	0.0				15	8 Sets - Data Default
1	2	1	0				16	
2	29	1	0				15	
1	0						16	
1	2	1	0				15	
2	29	1	0				16	
1	0						15	
1	2	1	0				16	
2	29	1	0				15	
1	0						16	
1	2	1	0				15	
2	29	1	0				16	
1	0						15	
1	2	1	0				16	
2	29	1	0				15	
1	0						16	
1	2	1	0				15	
2	29	1	0				16	
1	0						15	
1	2	1	0				16	
2	29	1	0				15	
1	0						16	
9.75726D+01		2.25614D-00					17	SV Mode No. 1 (Conv.)
1.02660D+02		4.00150D-00					15	SV Mode No. 2 (Conv.)
1	2	1	1				15A	
12345678901	2345678901	2345678901	2345678901	2345678901	2345678901	2345678901	1	

Two natural modes are sought in each frequency group and a record of the iteration progression is requested by setting IGEN = -2 in card 14. Starting conditions for seeking the natural modes are furnished by the user as indicated by IBEG = -1. The starting conditions are based on results of the stability analysis which was performed first (see Section 3.2.5). That analysis established that there is one natural mode in the first frequency group; however, because two sets of starting conditions are needed, the same set of starting conditions is repeated for a second time. There are two natural modes in the second frequency group.

Excitation in the present example is spatially fixed (ITYPE = 1 in card 14). It is represented by a unit force (1 lb.) at station 18 for the first frequency group but shifted to station 29 for the second frequency group (see card 16A).

3.2.5 Stability Analysis (IRUN = 5)

Example for the stability analysis deals with precisely the same rotor system as the above example except that the excitation system is not needed in the stability analysis. The stability analysis actually is included in the damped asynchronous response analysis if the option to do so is specified (IGEN $\neq$ 0 in card 14). The stability analysis is a shorter run because response calculation to a specific excitation is not performed. In the particular example, a relatively highly damped mode in the second frequency group required repeated trials before a fully converged solution is established; therefore, the stability analysis was actually completed first, then the damped asynchronous response was executed with starting conditions which are the results of the stability analysis.

Again, because the same speed-frequency combinations as for the asynchronous resonance calculation are used, Level I calculations are bypassed by accessing the pre-stored intermediate data file.

The first trial for the stability analysis was run with the input set-up listed in Table 10. Printing of Level II bearing data is suppressed with $IPRI = -1$. Two natural modes are sought in each frequency group (which is associated with one of two speed groups) and a record of the iteration is requested by setting $IGEN = -2$ in card 14. Since no specific clue is available for starting the iterative processes, the default for the internal starting logic is accepted with $IBEG = 0$ in card 14. The rest of the input list concerns Level II bearing data for each speed group.

The first trial yielded one damped natural mode in each frequency group. According to the pattern of the iteration progression, it was surmised that there is only one mode in the first frequency group and that the second frequency group may have two natural modes but the internal limits of the iteration process had prevented convergence to the second mode. Therefore, a second trial was carried out with the input listing of Table 11. User's prerogative to specify the starting values is requested with $IBEG = -1$ in card 14. The starting values of frequency and damping are furnished as card 17 for each mode in each frequency group. In the first frequency group, because a second mode is not expected, the same starting values are repeated. In the second frequency group, the starting values for the second mode (of the second frequency group) are those which would be continued by the iterative process if it had not been terminated. A full discussion on the record of iteration is provided in Section 3.4.5. The second trial still did not reach full convergence; however, the general trend previously noted was reaffirmed and the need for an "accelerated" change in the damping value was quite apparent. Therefore, a third trial with the starting damping value somewhat "accelerated" beyond the last step of iteration is used as shown in Table 12. Full convergence was indeed realized in the third trial.

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EXAMPLE OF INPUT GAIA FOR STABILITY ANALYSIS

FIRST CRUIAL WITH INTERNALLY DETERMINED STARTING VALUES

[illegible]

TABLE 11

[illegible]

EXAMPLE OF INPUT DATA FOR STABILITY ANALYSIS
THIRD TRIAL WITH USER-FURNISHED STARTING VALUES

[illegible]

3.3 Output Description

The output of the computer program consists of printouts of the input data with appropriate headings and of dynamic responses. Intermediate results of computations can also be printed out -- these printouts are controlled by the diagnostic parameters specified in the input setup. In the following, descriptions of the output emphasize its overall organization and contain supplementary definitions for the terminology appearing in the headings. Item numbers on the following pages refer to the "Item Number" column on the computer printouts given in Tables 13 through 20.

A. SUMMARY OF ROTOR MODEL

Items 1.0 through 4.0 summarize the rotor model input data. They are formulated under self-explanatory headings to allow convenient visual checking. The program checks logical aspects of the corresponding input setup. If an error is detected, an error message is written out and further execution is halted.

Item 5.0 gives static journal bearing load distributions, rotor weight, and the axial location of its center of gravity.

Item 1.0 Title and Summary

The title is printed out in the first line. It is followed by the summary of the input data for the rotor model; namely,

Shaft Segment:

Number of consecutive shaft segments of uniform cross section in the rotor model. (The numbering of nodal stations starts from the beginning of the first segment to the end of the last segment).

Shaft Materials:

Number of different sets of material properties, including weight density, Young's modulus, and shear modulus.

Lumped Inertia Stations:

Number of stations where concentrated inertia properties (in addition to the distributed mass in the shaft elements) have been assigned.

Bearings:

Number of stations where radial and/or angular stiffness may be assigned.

Item 2.0 Shaft Dimensions

They are tabulated in six columns:

Element No.: index number in the tabulation loop.

Length (in.): length of the individual shaft segment.

I.D. (in.): inner diameter for calculating flexural rigidity.
O.D. (in.): outer diameter for calculating flexural rigidity.
M.I.D. (in.): "mass inner diameter" used for calculating mass distribution.
M.O.D. (in.): "mass outer diameter" used for calculating mass distribution.

Item 3.0 Shaft Materials

There are four columns in the table:

Starting Node: segment number at which the present material data set begins to apply until the next data set appears.

Density (lbs./cu.-in.): weight density.

Young's Mod (psi): Young's modulus.

Shear Mod (psi): shear modulus.

3.1 Error Message

If the first line in the above tabulation does not refer to the first shaft element, an error message will be written out and further execution will be halted.

Item 4.0 Lumped Inertias

Following the heading, there are five columns:

Nodal Station: nodal station number at which the present set of lumped inertias is assigned.

Weight (lb.): weight of an additional rigid body attached to the designated nodal station.

Polar Inertia: weight polar moment of inertia of the attached rigid
(lb.-in.²) body.

Trans. Inertia: weight transverse moment of inertia of the attached rigid
(lb.-in.²) body.

CG Offset (in.): axial location of the center of gravity of the attached rigid body relative to the nodal station.

4.1 Error Message

If a nodal station number in the above tabulation exceeds the available range, an error message will be written out and further execution will be halted.

Item 5.0 Bearing Load Distribution

Static bearing loads due to gravity and misalignment are calculated according to static bearing data entered. This group of output is bypassed if no bearing is indicated (LBEA = 0 in the input). If only one bearing is detected, static equilibrium will not be possible, thus the program will write an error message and stop execution. If zero radial bearing stiffness is assigned to a designated bearing station in either direction, a default value of 0.1 lbs./in. will be assigned and an "attention message" will be printed out.

Numerical tabulation contains:

Brg. No.:	bearing index number.
St. No.:	station number assigned to each bearing.
Location (in.):	axial location of the bearing.
Vertical Plane:	misalignment, load, and moment in the vertical plane.
Horizontal Plane:	misalignment, load, and moment in the horizontal plane.

The tabulation is followed by the total weight and the axial location of the center of gravity.

B. SUMMARY OF DYNAMIC DATA (LEVEL 1)

Item 6.0 Number of Speed Groups

This statement gives the number of speed groups treated in the particular calculations as specified by the parameter NCASE of input card 1. It also indicates the number of times Items 8.0 through 13.0 will appear.

Item 7.0 Type of Vibration

This statement identifies whether the computation pertains to torsional vibration, bending vibration, or both as determined by the control parameter, LTYP, given by input card 3.

Item 8.0 Speed Group Number

This heading applies to Items 9.0 through 13.0 to follow.

Item 9.0 Excitation Frequencies

Frequency group number is indicated and the frequencies of the group in Hz are printed out. This item is omitted for synchronous cases as dictated by LRUN = 1 in input card 10.

C. LEVEL I DYNAMIC RESULTS

Item 10.0 Torsional Response Data

If the value of 1 is assigned to the parameter LTYP in input card 3, calculations pertaining to torsional vibrations only will be performed. The following group of output will be printed for each of the excitation frequencies one at a time. This group of output will be suppressed if the value of 3 is assigned to LTYP to treat both torsional and bending vibrations; instead, the torsional results will then be described in terms of the "Holzer" stiffness (see Item 12.0).

10.1

The dynamic torsional response distribution for all nodal stations due to a unit twist moment applied at the end of the rotor is listed. A new page is used for listing these data. In the event that a no-twist (null torsional displacement) condition is calculated, an alert message is written, saying

"END NODE IS STATIONARY AT #,###E ## HZ

TORS STIFF BELOW IS END TORQUE PER UNIT TWIST OF FIRST NODE."

Captions preceding the tabulation contain:

Frequency (Hz):	Frequency of torsional excitation.
Node No.:	The station number at which the exciting torque is applied. The last station number is printed here.
Location (in.):	Axial location of the above node.
Tors. Stiff: (in.-lb./rad.)	The dynamic torsional stiffness at the excitation point. In the event that the above-described alert message had been written out, the definition given there applies.

Response at each node is tabulated as follows:

Node:	Station number at which the response is indicated.
Location (in.):	Axial location of station.

Relative Twist: Normalized torsional displacement. In this listing the peak torsional displacement is used as the scale for normalization.

The actual twist per unit excitation torque is:

$$\frac{\text{RELATIVE TWIST (present station)}}{\text{RELATIVE TWIST (end)} \cdot \text{TORS. STIFF.}}$$

If the rotor end is a stationary point as indicated by the alert message then the above formula is replaced by:

$$\frac{\text{RELATIVE TWIST (present station)}}{\text{RELATIVE TWIST (first station)} \cdot \text{TORS. STIFF.}}$$

Unit Twist Rate: Local twist rate per unit excitation torque
(rad./in.-lb.) (applied at the end of the rotor).

10.2

The dynamic torsional response distribution at selected response stations due to a unit twist moment applied at each selected excitation station is listed.

The selected stations are all those identified in input card 8. Torsional excitation stations are those with the corresponding value of "Excitation Type Index", K8(I) = 2, 5, 6 or 8 in input card 9. A new page is used for each excitation station. Three special conditions can exist to cause a corresponding alert message to be written. If the excitation station is found to be stationary, either rotor half (aft or fore) must also be stationary. This condition is recognized as (1) fore-segment resonance or (2) aft-segment resonance. The alert message is written out, including the required special definition for "Tors. Stiff." For condition (3), torsional resonance of the system, the alert message is also written out.

Appropriate captions precede the listing of response distribution. A four-column response tabulation is the same as previously described except that only the selected response stations are included. The relative twist is normalized at the excitation station except for the three special cases discussed above. For fore-segment resonance, the twist at the first station is taken to be unity. For aft-segment resonance, the twist at the rotor end is taken to be unity. For torsional resonance, the peak twist is taken to be unity.

Item 11.0 Bending End Determinants

"Myklestad" determinants or end determinants of the bending problem are listed under appropriate headings of the frequency range in concern. For the synchronous case as designated by LRUN = 1 in input card 10, each frequency (Hz) should be precisely 1/60 times speed (RPM). Co-rotational and counter-rotational determinants are separately listed. This listing is omitted if LTYP = 1 in input card 3; i.e., if torsional response only is calculated.

Examination of this listing for a change of sign of the end determinant allows one to locate the critical speed (for the synchronous problem) or the resonant frequency (for the asynchronous problem) approximately without performing Level II computations.

Item 12.0 Torsional End Stiffness

"Holzer" stiffness or end stiffness of the torsional problem is listed alongside the frequency of excitation. This output is activated only when the parameter LTYP in input card 3 is given the value 3 to designate both torsional and bending calculations and the parameter LRUN in input card 10 is set to 0 for asynchronous calculations.

Examinations of this listing for a change of sign of the torsional end stiffness allows one to locate the torsional resonance frequency. No other provision is made to determine the torsional resonance frequency in this program.

Item 13.0 Level I Dynamic Bearing Data

Dynamic bearing data, as used in Level I (isotropic representation), are tabulated under headings of bearing number, station number, location measured from left end of rotor (axial distance), radial stiffness and angular stiffness. One set is given for each speed. This output is omitted if only torsional calculations are performed (LTYP = 1 in input card 3) or if so designated by the user (LPRI = -1 in input card 3).

D. LEVEL II DATA

Item 14.0 Calculation Summary

The following messages are printed out:

- an alphanumeric string giving the job identification and job title as entered in input card 2;
- Level II run mode according to IRUN (see descriptions under input card 14);
- type of excitation (for IRUN = 4 only) according to ITYPE (input card 14); and
- under respective headings, station numbers at which torsional and/or bending excitations are applied according to input cards 8 and 9 are listed.

These messages together with Items 6.0 through 9.0 describe the overall content of the dynamic results.

Item 15.0 Tabulation of Level I Matrices

Matrices are printed out for each speed-frequency combination if the parameter IDIAG of input card 14 is set to the value 2.

15.1

If torsional calculation is performed (LTYP = 1 or 3 in input card 3) the torsional mobility and impedance matrices are printed out in succession. The torsional matrices are speed independent and are thus printed out for distinct frequencies only.

15.2

If bending calculations are performed (LTYP = 2 or 3 in input card 3), the following bending matrices are listed under their corresponding headings in sequence.

- Level I bending mobility matrix in the Cartesian representation.
- Level I bending impedance matrix in the Cartesian representation (omitted if torsional calculation is not performed because Item 15.3 would contain the bending impedance only).

15.3

Level I impedance summary contains the following information:

- job identification
- job title
- speed in revolutions per second
- excitation frequency in Hz, and
- the total number of degrees of freedom

The consolidated bending-torsional impedance matrix is printed out on a new page. The bending impedance matrix is in the Cartesian representation and is in the upper left corner. The torsional impedance matrix is in the lower right corner.

Item 16.0 Level II Bearing Data

This set of output is omitted if both LBEA (input card 3) and IBRG (input card 14) are zero.

Under captions of speed (revolutions per minute) and excitation frequency (Hz), bearing data are tabulated under appropriate headings. A separate line is written for each bearing. If the bearing is capable of rendering both angular and translational restraints, the angular characteristics of the bearing are written after its translational characteristics. The headings of the table are self-explanatory. Each line contains the following information:

- bearing index number (line number in table).
- station number of bearing in rotor model.
- radial or angular bearing.
- eight matrix coefficients of the bearing,

K = stiffness coefficient

B = damping coefficient

The units of K are in (lb./in.) for a radial bearing and in units of (in.-lb./rad.) for an angular bearing. The units of B are those of K times seconds.

Item 17.0 Level II Bending Impedance Data

Impedance matrices including Level II bearing data are printed out if the parameter IDIAG is set to 2 in card 14.

17.1

Bending impedance matrix with Level II bearing data is printed in the Cartesian representation provided IBRG (input card 14) is not zero.

17.2

Bending impedance matrix with Level II bearing data is printed in rotating coordinates.

E. LEVEL II OUTPUTS -- RESULTS OF DYNAMIC BENDING ANALYSIS

This set of output covers 5 different modes of dynamic analysis corresponding to IRUN = 1 to 5 (input card 14). The 5 modes are:

- (i) Critical speed (IRUN = 1)
- (ii) Unbalance response (IRUN = 2)
- (iii) Asynchronous resonance (IRUN = 3).
- (iv) Asynchronous response (IRUN = 4).
- (v) Stability analysis (IRUN = 5).

(i) and (iii) are for undamped systems while (ii), (iv), and (v) are for damped systems. A description of each case is given in the following.

Item 18.0 Critical Speed Calculation

Following the heading "Critical Speed Determinants," the determinants of the impedance matrices are tabulated versus the corresponding frequencies. The changes of sign signify the existence of natural frequencies.

For critical speed calculation, only co-rotational (forward whirl) is considered. The number of co-rotational roots found is indicated.

The tabulation of mode shape consists of four columns. The first column gives the natural frequency. The second column shows the axial location of each excitation station. The third and fourth columns give the corresponding deflection and slope (as appropriate for the station, see Section 3.1). These are normalized with respect to the maximum deflection and slope.

Item 19.0 Unbalance Response

19.1

The excitation data and the corresponding response orbit are tabulated at each rotor speed. Since this is a synchronous case, speed (rpm) = 60 x frequency (Hz). The excitation data include the index number, the station number, the type of excitation (force or moment), and the orientation. The unbalance excitation is always a forward whirl; however, at each excitation point, there may be a distinct phase angle based on a reference point on the shaft which can be chosen by the user.

The response orbit at each station is, in general, of elliptical shape. The response ellipses can well be described by four spatial parameters: major and minor radii, inclination angle, and one time-related parameter (the phase reference angle). In the output a quantity, the ellipticity, which can be derived from the first two is also provided.

The major and minor radii set the size of the ellipse. The inclination angle is the angle between the major axis and the horizontal axis. The ellipticity is defined as the ratio between the difference of the two radii (major and minor) and the sum of them; if the ratio is greater than one, its reciprocal is used. Hence, a zero ellipticity implies a circular orbit while a unit ellipticity defines a straight line. The time-related phase reference angle at the station is measured with respect to the time reference point chosen by the user. This angle is that between the axial plane passing through both the z axis and reference point and the axial plane passing through both the z axis and displaced center of the rotor. The angle is positive when the displaced center of the rotor leads the reference point.

19.2

Iteration record of the complex eigenvalue calculation is printed out if the parameter IGEN of card 14 is a negative integer. The absolute value of IGEN represents the number of damped natural modes to be sought in each speed group, and its negative sign requests that the record of iteration be included in the output.

The iteration record consists of nine columns. The first column, under the heading "I" counts the number of iteration cycles which have been executed. The next two columns are respectively current estimates of the natural frequency (Hz) and the system damping (lb.-sec./in.). For the unbalance response problem, the synchronous constraint is imposed; therefore, the natural frequency is simply (1/60) of the damped critical speed. Modal mass and critical damping ratio occupy the next two

columns, they are defined in Section 6.2. Estimated corrections of the natural frequency and the system damping are indicated in columns 6 and 7. The computer program restricts the iterative process to a confined frequency range; therefore, actual change of the natural frequency for the next cycle of iteration may be only a fraction of the estimated correction; when this happens, the change of damping is proportionally reduced. Under the heading "Residue" the sum of squares of real and imaginary parts of the residue is listed. "D Check" heads up the "consistency parameter" given by Equation (6.18), it is used to achieve the correct factorization operation if another eigenvalue in the same frequency range is to be sought.

While the internal logic of the computer program to verify convergence is quite reliable, premature termination of the iterative process can occur. Display of the iteration record allows the user to decide whether or not an additional "search" effort is warranted. Typically, if a trend of monotonic decrease of "Residue" is shown while the iterative process is interrupted by internally set limits, another trial should be made with either or both of the following options:

- Shift the frequency range if one of the frequency bounds is repeatedly reached.
- Use user furnished starting values which are extrapolated from the current iteration record.

The iteration record also allows the user to verify if all the necessary convergence conditions are satisfied; i.e.,

- The value of "Residue" should be reducing by larger amounts upon approaching convergence.
- Estimated corrections of frequency and damping are small in comparison with their current values.
- The modal mass is approaching a positive limiting value.
- "D Check" is becoming stabilized.

The computer program presently tests the first two conditions.

19.3

The damped natural mode shape, accompanied by the listing of speed, frequency, and critical damping ratio, is tabulated in the same manner as the response orbit and is printed at each frequency point for every mode found in the designated speed range. This calculation may be suppressed if the parameter IGEN in input card 14 is set to zero.

The resonant response including excitation data is also tabulated in the same way as the response orbit. For a non-conservative system (e.g., a system with significant damping) the resonant response of the rotor can be quite different from its corresponding natural mode shape.

Item 20.0 Asynchronous Resonance

The set of output is similar to that of critical speed calculations, except, in addition to co-rotational modes, counter-rotational modes are printed out. Also, the rotor speed is different from the excitation frequency.

Item 21.0 Asynchronous Response

The output of this case is similar to that of unbalance response except for the non-synchronism; namely, the rotor speed and the excitation frequency are different from each other and the excitation may be either forward and backward whirl components or vertical and horizontal components depending on the value assigned to the parameter ITYPE in input card 14.

21.1

Excitation data and response orbits at each combination of rotor speed and excitation frequency are printed out.

21.2

Iteration record of the complex eigenvalue calculation is printed out if the parameter IGEN of card 14 is a negative integer. Remarks under 19.2 are applicable except that the computation is performed at a fixed shaft speed while the sought natural frequency has no direct relationship with the shaft speed.

21.3

Results for the damped, asynchronous natural modes in each frequency group and resonant response are printed out. Again this calculation would be suppressed if IGEN = 0 on input card 14.

Item 22.0 Stability Analysis

The output of stability analysis is essentially that portion of Item 21.3 pertaining to the damped, asynchronous, natural modes. The iteration record described under 21.2 is also available in a stability analysis.

3.4 Output Samples

The output samples have been taken from computer runs made for the rotor defined by the data in Section 3.2. Each output sample corresponds to an input sample previously given.

3.4.1 Critical Speed (IRUN = 1)

The results of the critical speed analysis are listed in Table 13. Items 1 - 5 relate to various aspects of rotor data under self-explanatory headings. Items 6 - 13 summarize Level I results. The column of co-rotational end determinants shows a change of sign near 5920 rpm which should be the location of a critical speed. Although a change of sign is also indicated by the column of counter-rotational determinants, the counter-rotational motion is not excitable by rotor unbalance unless there is significant anisotropy in the rotor system. Item 14.0 is mainly an identification table. Item 16.0 lists the prevailing bearing data used in Level II analysis in the eight-coefficient format. In this case, the data of Level I bearings as described by Item 13.0 are retained. Item 18.0 summarizes the results associated with the established critical speeds. First, the determinants of the system represented by the selected action stations are listed alongside the speed. Then the mode shape, co-rotational in this case, is given in the normalized representation. The amplitude distribution is typical of a "flexible translational" mode. Peak amplitude is near mid-span. Motion at each of the two bearing stations is less than 1/5 of the peak amplitude. Symmetry about the mid-span is nearly preserved.

3.4.2 Unbalance Response (IRUN = 2)

A preliminary run limited to Level I (KRUN = 0 in input card 1) yielded results highlighted in Table 14. The important information is contained in the list of co-rotational determinants (Item 11.0). Reversal of sign is seen between 4243 rpm and 4931 rpm and also between 6662 rpm and 7743 rpm. Simple interpolation yields estimated critical speeds of 4350 rpm and 7000 rpm. They are expected to be respectively the first translational and angular modes.

TABLE 13

COMPUTER OUTPUT FOR CRITICAL SPEED ANALYSIS

(From Input Data of Table 4)

5 Sheets

LUND ROTOR WITH OVERHUNG DISK AND RIGID SUPPORT ON BALL BECS							Item Number
SHAFT SEGMENTS = 32							1.0
SHAFT MATERIALS = 1							
LUMPED INERTIA STATIONS = 18							
BEARINGS = 2							
SHAFT DIMENSIONS							2.0
SEGMENT NO	LENGTH (IN)	I D (IN)	O.D. (IN)	M.I.D. (IN)	M.O.D (IN)		
1	3.1496	0.0000	2.4724	0.0000	2.4724		
2	0.7874	0.0000	2.4724	0.0000	2.4724		
3	2.4016	0.0000	3.1496	0.0000	3.1496		
4	0.4291	0.0000	3.1496	0.0000	3.4803		
5	1.1417	0.0000	4.9016	0.0000	3.8189		
6	1.1417	0.0000	4.9016	0.0000	3.8386		
7	0.3976	0.0000	3.1496	0.0000	3.5000		
8	2.2244	0.0000	3.1496	0.0000	3.1496		
9	0.5276	0.0000	3.1496	0.0000	3.7087		
10	1.3387	0.0000	5.5118	0.0000	3.8976		
11	1.3387	0.0000	5.5118	0.0000	3.9764		
12	0.4961	0.0000	3.0866	0.0000	3.7795		
13	1.7914	0.0000	3.0866	0.0000	3.2283		
14	1.0040	0.0000	3.9764	0.0000	4.0551		
15	1.3741	0.0000	3.8583	0.0000	3.9370		
16	0.5787	0.0000	3.0866	0.0000	3.3465		
17	1.4449	0.0000	5.1969	0.0000	4.0157		
18	1.4449	0.0000	5.1969	0.0000	3.9094		
19	2.6850	0.0000	3.1496	0.0000	3.1496		
20	0.5983	0.0000	3.1496	0.0000	3.5039		
21	0.7402	0.0000	4.8819	0.0000	3.8386		
22	0.7402	0.0000	4.8819	0.0000	3.8189		
23	0.5669	0.0000	3.1496	0.0000	3.4646		
24	2.7677	0.0000	3.1496	0.0000	3.1496		
25	1.4449	0.0000	4.8819	0.0000	3.7008		
26	1.4449	0.0000	4.8819	0.0000	3.5433		
27	3.0669	0.0000	3.1496	0.0000	3.1496		
28	0.7874	0.0000	2.4724	0.0000	2.4724		
29	6.9485	0.0000	2.4724	0.0000	2.4724		
30	0.7233	0.0000	3.2071	0.0000	2.4409		
31	0.6890	0.0000	3.3071	0.0000	2.4016		
32	0.6890	0.0000	1.5748	0.0000	1.7323		

TABLE 13 (CONT.)

SHAFT MATERIALS										Item Number
STARTING DENSITY YOUNG'S MOD SHEAR MOD										3.0
MODE (LBS/CU-IN) (PSI) (PSI)										
1	0.2830	2.8508E 07	8.9520E 06							
LUMPED INERTIAS										4.0
MODAL STATION	WEIGHT (LB)	POLAR INERTIA (LB-SQ IN)	TRANS INERTIA (LB-SQ IN)	CG OFF-SET (IN)						
1	0.6600	1.3640	0.6820	0.0000						
5	10.2080	99.2310	48.4220	0.0000						
6	10.7800	0.9855	48.0810	0.0000						
7	10.0100	98.5490	48.0810	0.0000						
10	34.9580	698.7100	467.1700	0.0000						
11	34.8040	654.0400	448.4200	0.0000						
12	34.6500	697.3500	467.1700	0.0000						
17	12.6060	126.8500	66.1540	0.0000						
18	13.4640	127.1900	66.1540	0.0000						
19	12.9800	128.5600	66.8360	0.0000						
21	29.2380	473.3800	244.1600	0.0000						
23	29.4140	477.0600	244.5000	0.0000						
25	13.3760	130.2600	67.5180	0.0000						
26	14.2340	130.2600	67.8590	0.0000						
27	13.7280	131.2900	68.2000	0.0000						
30	13.8820	46.1350	23.8700	0.0000						
32	13.9480	46.0350	23.8700	0.0000						
33	0.6600	1.3640	0.6820	-0.1575						
*****VERTICAL PLANE*****										5.0
BRC ST	LOCATION (IN)	MISALGN (IN)	LOAD (LB)	MOM (IN-LB)	MISALGN (IN)	LOAD (LB)	MOM (IN-LB)	*****HORIZONTAL PLANE*****		
1	2	3.1496	0.000000	187.9521	0.0000	0.000000	0.0000	LOAD (LB)	MOM (IN-LB)	
2	29	37.8547	0.000000	225.3712	0.0000	0.000000	0.0000	0.0000	0.0000	
TOTAL WEIGHT = 4.1332E 02 (LB)										5.0
LOCATION OF C.G. = 2.2073E 01 (IN)										

TABLE 13 (CONT.)

[illegible]

TABLE 13 (CONT.)

*****CALCULATION SUMMARY*****											Item Number
TEST IRUN=1 LUND ROTOR WITH OVERHUNG DISK AND RIGID SUPPORT ON 3ALL BPCS											14.0
CRITICAL SPEED CALCULATION											
BENDING EXCITATION STATIONS											
2	11	18	29								
LEVEL 2 BEARING DATA											16.0
ROTATIONAL SPEED = 4 5000E 03 RPM FREQUENCY = 7 5000E 01 HZ											
BEARING	***	TYPE	***	XX	*****	XY	*****	YX	*****	YY	
NO. STN		RADIAL	ANGULAR	K	C	K	C	K	C		
1	2	*	*	7 7987E 05	0 0000E-01	0 0000E-01	0 0000E-01	0 0000E-01	7 7987E 05	0 0000E-01	
2	29	*	*	8 2618E 05	0 0000E-01	0 0000E-01	0 0000E-01	0 0000E-01	8 2618E 05	0 0000E-01	
LEVEL 2 BEARING DATA											
ROTATIONAL SPEED = 4 9333E 03 RPM FREQUENCY = 8 2222E 01 HZ											
BEARING	***	TYPE	***	XX	*****	XY	*****	YX	*****	YY	
NO. STN		RADIAL	ANGULAR	K	C	K	C	K	C		
1	2	*	*	7 8246E 05	0 0000E-01	0 0000E-01	0 0000E-01	0 0000E-01	7 8246E 05	0 0000E-01	
2	29	*	*	8 2852E 05	0 0000E-01	0 0000E-01	0 0000E-01	0 0000E-01	8 2852E 05	0 0000E-01	
LEVEL 2 BEARING DATA											
ROTATIONAL SPEED = 5 4083E 03 RPM FREQUENCY = 9 0139E 01 HZ											
BEARING	***	TYPE	***	XX	*****	XY	*****	YX	*****	YY	
NO. STN		RADIAL	ANGULAR	K	C	K	C	K	C		
1	2	*	*	7 8549E 05	0 0000E-01	0 0000E-01	0 0000E-01	0 0000E-01	7 8549E 05	0 0000E-01	
2	29	*	*	8 3128E 05	0 0000E-01	0 0000E-01	0 0000E-01	0 0000E-01	8 3128E 05	0 0000E-01	
LEVEL 2 BEARING DATA											
ROTATIONAL SPEED = 5 9291E 03 RPM FREQUENCY = 9 8818E 01 HZ											
BEARING	***	TYPE	***	XX	*****	XY	*****	YX	*****	YY	
NO. STN		RADIAL	ANGULAR	K	C	K	C	K	C		
1	2	*	*	7 8902E 05	0 0000E-01	0 0000E-01	0 0000E-01	0 0000E-01	7 8902E 05	0 0000E-01	
2	29	*	*	8 3450E 05	0 0000E-01	0 0000E-01	0 0000E-01	0 0000E-01	8 3450E 05	0 0000E-01	
LEVEL 2 BEARING DATA											
ROTATIONAL SPEED = 6 5000E 03 RPM FREQUENCY = 1 0833E 02 HZ											
BEARING	***	TYPE	***	XX	*****	XY	*****	YX	*****	YY	
NO. STN		RADIAL	ANGULAR	K	C	K	C	K	C		
1	2	*	*	7 9310E 05	0 0000E-01	0 0000E-01	0 0000E-01	0 0000E-01	7 9310E 05	0 0000E-01	
2	29	*	*	8 3826E 05	0 0000E-01	0 0000E-01	0 0000E-01	0 0000E-01	8 3826E 05	0 0000E-01	

TABLE 13 (CONT.)

CRITICAL SPEED DETERMINANTS					Item Number
SPEED	(RPM)	DETERMINANT			18.0
4.5000E 03		7.4142E 01			
4.9333E 03		2.4505E 01			
5.4083E 03		5.7031E 00			
5.9291E 03		-5.2299E-01			
6.5000E 03		-1.9644E 00			
CO-ROTATIONAL MODE					
	RPM	LOCATION (IN)	DEFLECTION	SLOPE	
	5.8657E 03	3.1456E 00	1.7640E-01		
		1.3539E 01	8.4602E-01		
		2.1567E 01	1.0000E 00		
		3.7855E 01	1.4037E-01		
NO OF CO-ROTATIONAL ROOTS = 1					

TABLE 14

COMPUTER OUTPUT FOR PRELIMINARY UNBALANCE RESPONSE ANALYSIS

(From Input Data of Table 5)

LUND ROTOR UNBALANCE RESPONSE WITH SOFT-MOUNTED DAMPER											Item Number
SHAFT SEGMENTS = 32											1.0
SHAFT MATERIALS = 1											
LUMPED INERTIA STATIONS = 18											
BEARINGS = 2											
NUMBER OF SPEED GROUPS = 1											6.0
DYNAMIC RESPONSE OF THE BENDING MODE											
SPEED GROUP NUMBER 1											7.0
SPEED FREQUENCY END DETERMINANTS											
CO-ROTATIONAL CTR-ROTATIONAL											8.0
2.000E 03 3.333E 01 2.15422E 13 2.078425E 13											
2.3246E 03 3.8744E 01 1.864353E 13 1.773822E 13											
2.7019E 03 4.5032E 01 1.501517E 13 1.399574E 13											
3.1405E 03 5.2341E 01 1.062206E 13 9.585269E 12											11.0
3.6502E 03 6.0836E 01 5.575487E 12 4.722123E 12											
4.2426E 03 7.0711E 01 2.816836E 11 -4.558320E 10											
4.9313E 03 8.2188E 01 -4.325013E 12 -3.657621E 12											
5.7316E 03 9.5527E 01 -6.473211E 12 -4.429604E 12											
6.6619E 03 1.1103E 02 -3.299339E 12 -3.242122E 11											
7.7432E 03 1.2905E 02 8.861613E 12 9.621702E 12											
9.0000E 03 1.5000E 02 3.219663E 13 2.120175E 13											
BRC NO 1 2 29											13.0
STN NO 3.1496E 00 3.7855E 01											
LOC (IN) RAD (LB/IN) ANG (IN-LB/RAD) RAD (LB/IN) ANG (IN-LB/RAD) RAD (LB/IN) ANG (IN-LB/RAD)											
2.000E 03 1.6000E 05 0.0000E-01 1.6000E 05 0.0000E-01											
2.3246E 03 1.6000E 05 0.0000E-01 1.6000E 05 0.0000E-01											
2.7019E 03 1.6000E 05 0.0000E-01 1.6000E 05 0.0000E-01											
3.1405E 03 1.6000E 05 0.0000E-01 1.6000E 05 0.0000E-01											
3.6502E 03 1.6000E 05 0.0000E-01 1.6000E 05 0.0000E-01											
4.2426E 03 1.6000E 05 0.0000E-01 1.6000E 05 0.0000E-01											
4.9313E 03 1.6000E 05 0.0000E-01 1.6000E 05 0.0000E-01											
5.7316E 03 1.6000E 05 0.0000E-01 1.6000E 05 0.0000E-01											
6.6619E 03 1.6000E 05 0.0000E-01 1.6000E 05 0.0000E-01											
7.7432E 03 1.6000E 05 0.0000E-01 1.6000E 05 0.0000E-01											
9.0000E 03 1.6000E 05 0.0000E-01 1.6000E 05 0.0000E-01											

The complete computer output for the unbalance response analysis is given in Table 15. Two speed groups are included, which respectively cover the range 4000 - 5000 rpm and the range 6000 - 8000 rpm. Level II bearing data (Item 16.0) in the eight coefficient format, together with the excitation description and response (Item 19.1) are tabulated together on the same page at each speed point. Note that unbalance is specified in units of (in.-oz.) in input card 16A but is represented by the corresponding centrifugal force at each speed in the output. Circularity in the response orbit is indicated by equal magnitudes of major and minor radii at all stations. The amplitude peaks mildly between 4230 rpm and 4349 rpm with a nearly symmetrical mode shape, corresponding to a unit unbalance (1 in.-oz.) near mid-span (station 18). Symmetry of the mode shape is reflected not only by the amplitude distribution but is also indicated by the nearly uniform phase reference. In the second speed group, the unit unbalance is shifted to station 29 which is a bearing support. This is done because an angular mode shape is anticipated. Peaking in the second speed group is observed between 6928 rpm and 7182 rpm, again very mildly. The angular mode shape is indicated by the difference in the phase reference of nearly 180 degrees between stations 2 and 29.

3.4.3 Asynchronous Resonance (IRUN = 3)

Two runs of asynchronous resonance analysis were made. The first run was limited to Level I, but dealt with both torsional and bending motions. The descriptive data of the rotor system have already been discussed in previous examples, the essential output of the present run are the lists of Item 11.0, the bending end determinants, and Item 12.0, the torsional end stiffness, which are tabulated one after another and followed by Level I bearing data, Item 13.0, within each speed-frequency group in Table 16. Change of sign indicates the location of a resonance condition. It is seen that bending asynchronous resonances of both co-rotational and counter-rotation types are located within each of the three frequency groups. Torsional resonance is found near 324 Hz.

TABLE 15
COMPUTER OUTPUT FOR UNBALANCE RESPONSE ANALYSIS
(From Input Data of Table 6)

23 Sheets

LUND ROTOR UNBALANCE RESPONSE WITH SOFT-MOUNTED DAMPER			Item Number
SHAFT SEGMENTS	=	32	1.0
SHAFT MATERIALS	=	1	
LUMPED INERTIA STATIONS	=	18	
BEARINGS	=	2	

TABLE 15 (CONT.)

NUMBER OF SPEED GROUPS = 2		DYNAMIC RESPONSE OF THE BENDING MODE		Item Number	
SPEED GROUP NUMBER		1		8.0	
SPEED (RPM)	FREQUENCY (HZ)	END DETERMINANTS		11.0	
4.0000E 03	6.667E 01	CO-ROTATIONAL	CTR-ROTATIONAL	6.0 7.0	
4.1131E 03	6.8552E 01	2.339302E 12	1.755535E 12		
4.2295E 03	7.0491E 01	1.357425E 12	8.863425E 11		
4.3491E 03	7.2495E 01	3.884523E 11	4.586776E 10		
4.4721E 03	7.4536E 01	-5.601040E 11	-7.576682E 11		
4.5986E 03	7.6644E 01	-1.479750E 12	-1.515250E 12		
4.7287E 03	7.8812E 01	-2.360931E 12	-2.217054E 12		
4.8625E 03	8.1041E 01	-3.192960E 12	-2.852458E 12		
5.0000E 03	8.3333E 01	-3.963935E 12	-3.410054E 12		
		-4.660675E 12	-3.877703E 12		
SPEED GROUP NUMBER		2		13.0	
BRC NO		1		3	
STN NO		2		4	
LOC (IN)		29			
SPEED (RPM)	RAD (LB/IN)	ANG (IN-LB/RAD)	ANG (IN-LB/RAD)	RAD (LB/IN)	ANG (IN-LB/RAD)
4.0000E 03	1.6000E 05	0.0000E-01	0.0000E-01	3.7855E 01	0.0000E-01
4.1131E 03	1.6000E 05	0.0000E-01	0.0000E-01	1.6000E 05	0.0000E-01
4.2295E 03	1.6000E 05	0.0000E-01	0.0000E-01	1.6000E 05	0.0000E-01
4.3491E 03	1.6000E 05	0.0000E-01	0.0000E-01	1.6000E 05	0.0000E-01
4.4721E 03	1.6000E 05	0.0000E-01	0.0000E-01	1.6000E 05	0.0000E-01
4.5986E 03	1.6000E 05	0.0000E-01	0.0000E-01	1.6000E 05	0.0000E-01
4.7287E 03	1.6000E 05	0.0000E-01	0.0000E-01	1.6000E 05	0.0000E-01
4.8625E 03	1.6000E 05	0.0000E-01	0.0000E-01	1.6000E 05	0.0000E-01
5.0000E 03	1.6000E 05	0.0000E-01	0.0000E-01	1.6000E 05	0.0000E-01

TABLE 15 (CONT.)

SPEED GROUP NUMBER		2		Item Number			
SPEED (RPM)		FREQUENCY (HZ)	END DETERMINANTS	8.0			
6.000E 03		1.000E 02	CO-ROTATIONAL CTR-ROTATIONAL	11.0			
6.2197E 03		1.0366E 02	-6.232070E 12 -3.784382E 12				
6.4474E 03		1.0746E 02	-5.638002E 12 -2.921234E 12				
6.6835E 03		1.1139E 02	-4.625200E 12 -1.721174E 12				
6.9282E 03		1.1547E 02	-3.145846E 12 -1.703442E 11				
7.1819E 03		1.1970E 02	-1.144314E 12 1.734439E 12				
7.4448E 03		1.2403E 02	1.430474E 12 3.981556E 12				
7.7174E 03		1.2862E 02	4.623807E 12 6.539538E 12				
8.0000E 03		1.3333E 02	8.470818E 12 9.350980E 12				
8.0000E 03		1.3333E 02	1.299069E 13 1.232531E 13				
BRG NO		1	2	13.0			
STM NO		2	29				
LOC (IN)		3.1496E 00	3.7855E 01				
SPEED (RPM)		RAD (LB/IN)	ANG (IN-LB/RAD)				
6.000E 03		1.6000E 05	0.0000E-01				
6.2197E 03		1.6000E 05	0.0000E-01				
6.4474E 03		1.6000E 05	0.0000E-01				
6.6835E 03		1.6000E 05	0.0000E-01				
6.9282E 03		1.6000E 05	0.0000E-01				
7.1819E 03		1.6000E 05	0.0000E-01				
7.4448E 03		1.6000E 05	0.0000E-01				
7.7174E 03		1.6000E 05	0.0000E-01				
8.0000E 03		1.6000E 05	0.0000E-01				
PAD (LB/IN)		ANG (IN-LB/RAD)	ANG (IN-LB/RAD)	4			
RAD (LB/IN)		ANG (IN-LB/RAD)	ANG (IN-LB/RAD)				
RAD (LB/IN)		ANG (IN-LB/RAD)	ANG (IN-LB/RAD)				
RAD (LB/IN)		ANG (IN-LB/RAD)	ANG (IN-LB/RAD)				
RAD (LB/IN)		ANG (IN-LB/RAD)	ANG (IN-LB/RAD)				
RAD (LB/IN)		ANG (IN-LB/RAD)	ANG (IN-LB/RAD)				
RAD (LB/IN)		ANG (IN-LB/RAD)	ANG (IN-LB/RAD)				
RAD (LB/IN)		ANG (IN-LB/RAD)	ANG (IN-LB/RAD)				
RAD (LB/IN)		ANG (IN-LB/RAD)	ANG (IN-LB/RAD)				
RAD (LB/IN)		ANG (IN-LB/RAD)	ANG (IN-LB/RAD)				

TABLE 15 (CONT.)

Item Number			Remarks
*****CALCULATION SUMMARY*****			
TEST IRUM-2B LUND ROTOR UNBALANCE RESPONSE WITH SOFT-MOUNTED DAMPER			
UNBALANCE RESPONSE			
BENDING EXCITATION STATIONS			
2	11	18 29	Speed Group No. 1

TABLE 15 (CONT.)

LEVEL 2 BEARING DATA										Item Number	Remarks
ROTATIONAL SPEED = 4.0000E 03 RPM											
FREQUENCY = 6.6667E 01 HZ											
BEARING ***** XX ***** XY ***** rX ***** YY *****										15.0	Speed Point No. 1 of 9
NO. STN TYPE **** K B K B K B											
1 5282E 05 1 0056E 02 0 0000E 01 0 0000E -01 0 0000E -01 0 0000E -01 1 5282E 05 1 0056E 02											
2 29 * 1 5282E 05 1 0056E 02 0 0000E -01 0 0000E -01 0 0000E -01 1 5282E 05 1 0056E 02											
EXCITATION DATA											
***** FORWARD ***** BACKWARD *****										19.1	
NO STN FORCE MOMENT IN-PHASE LAG IN-PHASE LAG											
1 2 * 0.0000E-01 0 0000E-01 0 0000E-01 0 0000E-01											
2 11 * 0 0000E-01 0.0000E-01 0 0000E-01 0 0000E-01											
3 18 * 2 8380E 01 0.0000E-01 0 0000E-01 0 0000E-01											
4 29 * 0.0000E-01 0 0000E-01 0 0000E-01 0 0000E-01											
RESPONSE ORBIT											
ROTATIONAL SPEED = 4.0000E 03 RPM											
FREQUENCY = 6.6667E 01 HZ											
***** PRINCIPAL RADII ***** INCLINATION ***** PHASE *****											
NO STN LOCATION DISPL SLOPE MAJOR MINOR (DEG) REFERENCE											
1 2 * 1496 * 4 8863E-04 4 8863E-04 2 7893E 01 -6 1270E 01											ELLIPTICITY
2 11 * 5395 * 8 2599E-04 8 2599E-04 2 8793E 01 -5 3658E 01											7 1004E-12
3 18 * 5673 * 9 0178E-04 9 0178E-04 2 9191E 01 -5 2653E 01											7 0230E-12
4 29 * 8547 * 4 9422E-04 4 9422E-04 2 9897E 01 -6 3138E 01											6 9406E-12
											6 6404E-12

TABLE 15 (CONT.)

LEVEL 2-BEARING DATA										Item Number	Remarks
ROTATIONAL SPEED = 4.1131E 03 RPM FREQUENCY = 6.8552E 01 HZ										16.0	Speed Point No. 2 of 9
BEARING *** TYPE ***											
NO. STN K 1.5282E 05 1.0056E 02 0.0000E-01 0.0000E-01 0											

TABLE 15 (CONT.)

LEVEL 2 BEARING DATA										Item Number	Remarks				
ROTATIONAL SPEED = 4 2295E 03 RPM FREQUENCY = 7 0491E 01 HZ										16.0	Speed Point No. 3 of 9				
BEARING		TYPE		XX		YY		YX				VY			
NO. STM		RADIAL ANGULAR		K		K		K				K			
1 2		1 5282E 05 1 0056E 02		0 0000E-01 0 0000E-01		0 0000E-01 0 0000E-01		0 0000E-01 0 0000E-01				1 5282E 05 1 0056E 02			
2 29		1 5282E 05 1 0056E 02		0 0000E-01 0 0000E-01		0 0000E-01 0 0000E-01		0 0000E-01 0 0000E-01		1 5282E 05 1 0056E 02					
EXCITATION DATA															
NO STM		TYPE		FORWARD		BACKWARD									
		FORCE MOMENT		IM-PHASE LAG		IN-PHASE LAG									
1 2		*		0 0000E-01 0 0000E-01		0 0000E-01 0 0000E-01									
2 11		*		0 0000E-01 0 0000E-01		0 0000E-01 0 0000E-01									
3 18		*		3 1730E 01 0 0000E-01		0 0000E-01 0 0000E-01									
4 29		*		0 0000E-01 0 0000E-01		0 0000E-01 0 0000E-01									
RESPONSE ORBIT										19.1					
ROTATIONAL SPEED = 4 2295E 03 RPM FREQUENCY = 7 0491E 01 HZ															
NO. STM		LOCATION		DISPL		SLOPE		PRINCIPAL PADI				INCLINATION		PHASE REFERENCE	
								MAJOR MINOR				(DEG)		ELLIPTICITY	
1 2		3 1496		*				6.3538E-04 6.3538E-04		4 2557E 01-9.0850E 01		9.9380E-12			
2 11		13.5395		*				1.0550E-03 1.0550E-03		4 4414E 01-8.2811E 01		9.9056E-12			
3 18		21.5673		*				1.1448E-03 1.1448E-03		4 5410E 01-8.1741E 01		1.0486E-11			
4 29		37.8547		*				6.3514E-04 6.3514E-04		4 6732E 01-9.3230E 01		9.9637E-12			

TABLE 15 (CONT.)

LEVEL 2 BEARING DATA										Item Number	Remarks
ROTATIONAL SPEED = 4.4721E 03 RPM FREQUENCY = 7.4536E 01 HZ											
BEARING NO.	TYPE	XX	YY	XY	XX	YY	XY	XX	YY	16.0	Speed Point No. 5 of 9
1	2	K	S	K	S	K	S	K	S		
1	2	1.5282E 05	1.0056E 02	0.0000E-01	0.0000E-01	0.0000E-01	0.0000E-01	0.0000E-01	0.0000E-01		
2	29	1.5282E 05	1.0056E 02	0.0000E-01	0.0000E-01	0.0000E-01	0.0000E-01	0.0000E-01	0.0000E-01		
EXCITATION DATA										19.1	
NO.	STN	LOCATION	FORCE	MOMENT	IN-PHASE	LAG	IN-PHASE	LAG	IN-PHASE		
1	2				0.0000E-01	0.0000E-01	0.0000E-01	0.0000E-01	0.0000E-01		
2	11				0.0000E-01	0.0000E-01	0.0000E-01	0.0000E-01	0.0000E-01		
3	18				3.5476E 01	0.0000E-01	0.0000E-01	0.0000E-01	0.0000E-01		
4	29				0.0000E-01	0.0000E-01	0.0000E-01	0.0000E-01	0.0000E-01		
RESPONSE ORBIT										19.1	
ROTATIONAL SPEED = 4.4721E 03 RPM FREQUENCY = 7.4536E 01 HZ											
NO	STN	LOCATION	DISPL	SLOPE	MAJOR	MINOR	PRINCIPAL RADII	INCLINATION	PHASE REFERENCE	ELLIPTICITY	
1	2	3.1496	*	*	6.1486E-04	6.1486E-04	5.7196E 01-1.2291E 02	(DEG)	5.7196E 01-1.2291E 02		
2	11	13.5395	*	*	1.0007E-03	1.0007E-03	5.9512E 01-1.1443E 02		5.9512E 01-1.1443E 02	6.8728E-12	
3	18	21.5673	*	*	1.0783E-03	1.0783E-03	6.0759E 01-1.1330E 02		6.0759E 01-1.1330E 02	7.2303E-12	
4	29	37.8547	*	*	6.0663E-04	6.0663E-04	6.3242E 01-1.2598E 02		6.3242E 01-1.2598E 02	7.2972E-12	

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TABLE 15 (CONT.)

LEVEL 2 BEARING DATA												Item Number	Remarks		
ROTATIONAL SPEED = 4.7287E 03 RPM FREQUENCY = 7.8812E 01 HZ															
BEARING NO. STN		TYPE		RADIAL ANGULAR		XX		XY		YX		16.0	Speed Point No. 7 of 9		
						K		K		K					
1	2	*		1.5282E 05	1.0056E 02	0.0000E-01	0.0000E-01	0.0000E-01	0.0000E-01	0.0000E-01	0.0000E-01				
2	29	*		1.5282E 05	1.0056E 02	0.0000E-01	0.0000E-01	0.0000E-01	0.0000E-01	0.0000E-01	0.0000E-01				
EXCITATION DATA												19.1			
ROTATIONAL SPEED = 4.7287E 03 RPM FREQUENCY = 7.8812E 01 HZ															
NO. STN		TYPE		FORCE		MOMENT		IN-PHASE		LAG		19.1			
								BACKWARD							
1	2	*		0.0000E-01	0.0000E-01	0.0000E-01	0.0000E-01	0.0000E-01	0.0000E-01	0.0000E-01	0.0000E-01				
2	11	*		0.0000E-01	0.0000E-01	0.0000E-01	0.0000E-01	0.0000E-01	0.0000E-01	0.0000E-01	0.0000E-01				
3	18	*		2.9663E 01	0.0000E-01	0.0000E-01	0.0000E-01	0.0000E-01	0.0000E-01	0.0000E-01	0.0000E-01				
4	29	*		0.0000E-01	0.0000E-01	0.0000E-01	0.0000E-01	0.0000E-01	0.0000E-01	0.0000E-01	0.0000E-01				
RESPONSE ORBIT												19.1			
ROTATIONAL SPEED = 4.7287E 03 RPM FREQUENCY = 7.8812E 01 HZ															
NO. STN		LOCATION		DISPL		SLOPE		PRINCIPAL RADII		PHASE		19.1			
								(DEG)							
1	2	*		3.1496	*			5.0253E-04	5.0253E-04	6.7150E 01	1.4396E 02			ELLIPTICITY	4.0043E-12
2	11	*		13.5395	*			7.9800E-04	7.9800E-04	6.9673E 01	1.3503E 02				4.3552E-12
3	18	*		21.5673	*			8.5488E-04	8.5488E-04	7.0838E 01	1.3384E 02				4.4886E-12
4	29	*		37.8547	*			4.8850E-04	4.8850E-04	7.3477E 01	1.4795E 02				4.5170E-12

TABLE 15 (CONT.)

LEVEL 2 BEARING DATA										Item Number	Remarks
ROTATIONAL SPEED = 4.8625E 03 RPM FREQUENCY = 8 1041E 01 HZ										16.0	Speed Point No. 4 of 9
BEARING TYPE XX YY K											

TABLE 15 (CONT.)

LEVEL 2 BEARING DATA										Item Number	Remarks
ROTATIONAL SPEED = 5.0000E 03 RPM FREQUENCY = 8 3333E 01 HZ											
BEARING TYPE XX XY YX K											

TABLE 15 (CONT.)

Item Number		Remarks
*****CALCULATION SUMMARY*****		
TEST IRUN=28 LUNG ROTOR UNBALANCE RESPONSE WITH SOFT-MOUNTED DAMPER		
UNBALANCE RESPONSE		
SENDING EXCITATION STATIONS		
2	11 18 29	
14.0		Speed Group No. 2

TABLE 15 (CONT.)

LEVEL 2 BEARING DATA		FREQUENCY = 1 0000E 02 HZ		Item Number	Remarks
ROTATIONAL SPEED = 6 0000E 03 RPM					
BEARING TYPE		***** XX ***** YV *****		16.0	Speed Point No. 1 of 9
NO. 8TH RADIAL ANGULAR		K			
1	2	1 4545E 05 9 1544E 01	0 0000E-01 0 0000E-01 0 0000E-01 1 4545E 05 9 1544E 01		
2	29	1 4545E 05 9 1544E 01	0 0000E-01 0 0000E-01 0 0000E-01 1 4545E 05 9 1544E 01		
EXCITATION DATA					
***** TYPE *****		***** FORWARD *****			
NO	SIN	FORCE	MOMENT	IN-PHASE	LAG
1	2	*		0 0000E-01 0 0000E-01	0 0000E-01
2	11	*		0 0000E-01 0 0000E-01	0 0000E-01
3	18	*		0 0000E-01 0 0000E-01	0 0000E-01
4	29	*		6 3856E 01 0 0000E-01	0 0000E-01
RESPONSE ORBIT					
ROTATIONAL SPEED = 6 0000E 03 RPM		FREQUENCY = 1 0000E 02 HZ		19.1	
***** TYPE *****					
NO	SIN	LOCATION	DISPL	SLOPE	PHASE
1	2	3 1496	*	4.4769E-04 4 4769E-04	0 0000E-01 1 2832E 02
2	11	13 5395	*	3.9782E-04 3 9782E-04	6 8696E 01 1 4868E 02
3	18	21 5673	*	2.5284E-04 2 5284E-04	8 7245E 01 1 7340E 02
4	29	72 5642	*	5.8932E-04 5 8932E-04	7 1002E 00 5 6845E 01

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TABLE 15 (CONT.)

LEVEL 2 BEARING DATA		FREQUENCY = 1 0366E 02 HZ		Item Number	Remarks
ROTATIONAL SPEED = 6 2197E 03 RPM					
BEARING	TYPE	XX	YY	16.0	Speed Point No. 2 of 9
NO. STN	RADIAL ANGULAR	K	B		
1 2	*	1 4545E 05 9 1544E 01	0 0000E-01 0 0000E-01		
2 29	*	1 4545E 05 9 1544E 01	0 0000E-01 0 0000E-01		
EXCITATION DATA		FREQUENCY = 1 0366E 02 HZ			
NO	SIN	TYPE	MOMENT		
1 2	*	***	FORWARD		
2 11	*	***	BACKWARD		
3 18	*	***	BACKWARD		
4 29	*	***	BACKWARD		
RESPONSE ORBIT		FREQUENCY = 1 0366E 02 HZ		19.1	
ROTATIONAL SPEED = 6 2197E 03 RPM					
NO	SIN	LOCATION	DISPL	SLOPE	PHASE
1 2	3	1496	*		ELLIPTICITY
2 11	13	3395	*		REFERENCE
3 18	21	5673	*		(DEG)
4 29	37	9547	*		MINOR
					MAJOR
					INCLINATION
					PHASE
					REFERENCE
					ELLIPTICITY
					REFERENCE
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TABLE 15 (CONT.)

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TABLE 15 (CONT.)

Item Number		Remarks	
LEVEL 2 READING DATA			
ROTATIONAL SPEED = 6 5835E 03 RPM		FREQUENCY = 1 1139E 02 HZ	
BEARING TYPE DATA			
MC. STN RADIAL ANGULAR		K	
1	2	1 4545E 05 1 1544E 01	1 4545E 05 1 1544E 01
2	2	1 4545E 05 1 1544E 01	1 4545E 05 1 1544E 01
EXCITATION DATA			
**** FORCE ****		**** DISPLACEMENT ****	
NO	STN	IN-PHASE	LAG
1	2	0 0000E-01 0 0000E-01	0 0000E-01 0 0000E-01
2	11	0 0000E-01 0 0000E-01	0 0000E-01 0 0000E-01
3	18	0 0000E-01 0 0000E-01	0 0000E-01 0 0000E-01
4	22	7 9232E 01 0 0000E-01	7 9232E 01 0 0000E-01
RESPONSE DATA			
ROTATIONAL SPEED = 6 6335E 03 RPM		FREQUENCY = 1 1139E 02 HZ	
**** PRINCIPAL RADIAL **** INCLINATION **** PHASE ****			
NO	STN	LOC. IN DISPL SLORE	MAJOR MINOR DEG REFERENCE
1	2	17 1196	5 3785E-04 5 3785E-04
2	11	13 5395	3 9823E-04 3 9823E-04
3	18	21 5673	1 9809E-04 1 9809E-04
4	22	37 8547	9 1092E-04 9 1092E-04
ELLIPTICITY			
		5 3714E-13	
		5 4465E-13	
		1 7690E-12	
		3 1893E-13	
16.0		K	
19.1		K	

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TABLE 15 (CONT.)

Item Number		Remarks
LEVEL 2 BEARING DATA		
ROTATIONAL SPEED = 7 1819E 03 RPM		FREQUENCY = 1 1970E 02 HZ
BEARING TYPE DATA		
NO. STN	K	YX
1 2	1 4545E 05 9 1544E 01	0 0000E-01 0 0000E-01 1 4545E 05 9 1544E 01
2 29	1 4545E 05 9 1544E 01	0 0000E-01 0 0000E-01 1 4545E 05 9 1544E 01
EXCITATION DATA		
NO. STN	FORCE	MOMENT
1 2	0 0000E-01	0 0000E-01 0 0000E-01
2 11	0 0000E-01	0 0000E-01 0 0000E-01
3 16	0 0000E-01	0 0000E-01 0 0000E-01
4 29	9 1490E 01	0 0000E-01 0 0000E-01
RESPONSE ORBIT		
ROTATIONAL SPEED = 7 1819E 03 RPM		FREQUENCY = 1 1970E 02 HZ
NO. STN	LOCATION	DIAPL. SHAPE
1 2	3 1496	5 2174E-04 5 2174E-04 6 4804E 01 6 6173E 01
2 11	13 5395	3 4128E-04 3 4128E-04 7 5597E 01 8 9973E 01
3 18	21 5673	1 5230E-04 1 5230E-04 -6 9453E 01 1.5347E 02
4 29	37 8547	9 9734E-04 9 9734E-04 3 3115E 01-1 0708E 02
ELLIPTICITY		
3 9899E-13		
8 4379E-13		
1 6972E-12		
1 3915E-13		
19.1		

TABLE 15 (CONT.)

Item Number		Remarks
LEVEL 2 BEARING, CAT ROTATIONAL SPEED = 7.4448E 03 RPM PREQUENCY = 1.2408E 04 HZ		
BEARINGS TYPE ANGLE K XY YX YY ZZ NO. STN RADIAL ANGULAR K K K K K 1 2 * 1.4545E 05 9.1544E 01 3.0000E-01 0.0000E-01 0.0000E-01 1.4545E 05 9.1544E 01 2 29 * 1.4545E 05 9.1544E 01 3.0000E-01 0.0000E-01 0.0000E-01 1.4545E 05 9.1544E 01		
EXCITATION DATA *** TYPE *** *** FORWARD *** *** BACKWARD *** NO STN FORCE MOMENT IN-PHASE LAG IN-PHASE LAG 1 2 * 0.0000E-01 0.0000E-01 0.0000E-01 0.0000E-01 0.0000E-01 0.0000E-01 2 11 * 0.0000E-01 0.0000E-01 0.0000E-01 0.0000E-01 0.0000E-01 0.0000E-01 3 12 * 0.0000E-01 0.0000E-01 0.0000E-01 0.0000E-01 0.0000E-01 0.0000E-01 4 29 * 0.0000E-01 0.0000E-01 0.0000E-01 0.0000E-01 0.0000E-01 0.0000E-01		
RESPONSE ORBIT ROTATIONAL SPEED = 7.4448E 03 RPM FREQUENCY = 1.2408E 04 HZ 19.1		
** PRINCIPAL PAULI ** INCLINATION PHASE NO STN LOCATION DISPL SLOPE MAJOR MINOR REFERENCE ELLIPTICITY 1 2 3 1496 * 4.8411E-04 4.8411E-04 4.0119E 01 5.3331E 01 4.3000E-14 2 11 13 5795 * 2.9715E-04 2.9715E-04 5.8865E 01 7.7885E 01 9.3407E-14 3 18 21 5673 * 1.3270E-04 1.3270E-04 -2.9605E 01 1.5390E 02 1.8301E-13 4 29 37 8547 * 9.7544E-04 9.7544E-04 2.0911E 01 1.1895E 02 2.1341E 14		

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1

TABLE 15 (CONT.)

[illegible]

TABLE 15 (CONT.)

Item Number		Remarks	
LEVEL 2 BEARING 1.1TH			
ROTATIONAL SPEED = 8 0000E 03 RPM		FREQUENCY = 1 2313E 01 HZ	
BEARING TYPE		K	
NO. STM		K	
RADIAL ANGULAR		K	
1	2	1 4545E 05 9 1544E 01	0 0000E-01 0 0000E-01 1 4545E 03 9 1544E 01
2	2	1 4545E 05 9 1544E 01	0 0000E-01 0 0000E-01 1 4545E 05 9 1544E 01
16.0		Speed Point No. 9 of 9	
EXCITATION DATA			
NO STM		K	
FORCE MOMENT		K	
1	2	0 0000E-01 0 0000E-01 0 0000E-01 0 0000E-01	0 0000E-01 0 0000E-01 0 0000E-01 0 0000E-01
2	11	0 0000E-01 0 0000E-01 0 0000E-01 0 0000E-01	0 0000E-01 0 0000E-01 0 0000E-01 0 0000E-01
3	18	0 0000E-01 0 0000E-01 0 0000E-01 0 0000E-01	0 0000E-01 0 0000E-01 0 0000E-01 0 0000E-01
4	29	1 1352E 02 0 0000E-01 0 0000E-01 0 0000E-01	0 0000E-01 0 0000E-01 0 0000E-01 0 0000E-01
RESPONSE ORBIT			
ROTATIONAL SPEED = 8 0000E 03 RPM		FREQUENCY = 1 2313E 01 HZ	
NO STM		K	
LOCATION		K	
DISPL		K	
SLOPE		K	
1	2	3 9818E-04 3 9818E-04 2 1818E 01 3 2176E 01	2 6913E-14
2	11	2 0849E-04 2 0849E-04 3 4830E 01 5 2503E 01	5 8244E-14
3	18	1 0877E-04 1 0877E-04 -3 3412E 01 1 5945E 02	2 3922E-14
4	29	8 6306E-04 8 6306E-04 7 2847E 01-1 3549E 02	3 2159E-14
19.1			

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TABLE 16

PARTIAL OUTPUT OF ASYNCHRONOUS RESONANCE ANALYSIS FOR TORSIONAL AND BENDING MOTIONS

LEVEL 1 ONLY

(From Input Data of Table 7)

3 Sheets

LUND MOTOR WITH SIMULATED FLUID FILM BRGS AND TORS ANALYSIS			Item Number
SHAFT SEGMENTS	=	32	1.0
SHAFT MATERIALS	=	1	
LUMPED INERTIA STATIONS	=	18	
BEARINGS	=	2	

TABLE 16 (CONT.)

NUMBER OF SPEED GROUPS = 2										Item Number
DYNAMIC RESPONSES OF BOTH TORSIONAL AND BENDING MODES										6.0
										7.0
SPEED GROUP NUMBER 1										8.0
EXCITATION FREQUENCY GROUP 1										9.0
HZ 63.0000 64.6396 66.3218 68.0478 69.8187 71.6357 73.5000										
SPEED (RPM)		FREQUENCY (HZ)		END DETERMINANTS						
				CO-ROTATIONAL CTR-ROTATIONAL						
8.0000E 03	6.3000E 01	2.515243E 12		1.548479E 12						11.0
8.0000E 03	6.4640E 01	1.747326E 12		9.578401E 11						
8.0000E 03	6.6322E 01	9.827314E 11		3.824287E 11						
8.0000E 03	6.8048E 01	2.258965E 11		-1.735230E 11						
8.0000E 03	6.9819E 01	-5.181722E 11		-7.053880E 11						
8.0000E 03	7.1636E 01	-1.243858E 12		-1.208133E 12						
8.0000E 03	7.3500E 01	-1.944890E 12		-1.676312E 12						
FREQUENCY (HZ)		TORSIONAL								
		END STIFF								
6.3000D 01	-1.611507D 06									12.0
6.4640D 01	-1.690822D 06									
6.6322D 01	-1.773718D 06									
6.8048D 01	-1.860323D 06									
6.9819D 01	-1.950763D 06									
7.1636D 01	-2.045162D 06									
7.3500D 01	-2.143647D 06									
BRG NO		1								
STN NO		2								
LOC (IN)		3.1496E 00								4
SPEED (RPM)		RAD		3.7855E 01		RAD		ANG		
		(LB/IN)		(LB/IN)		(IN-LB/RAD)		(LB/IN)		
8.0000E 03		1.2950E 05		0.0000E-01		0.0000E-01		1.5350E 05		
		ANG		ANG		ANG		ANG		
		(IN-LB/RAD)		(LB/IN)		(IN-LB/RAD)		(IN-LB/RAD)		
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TABLE 16 (CONT.)

SPEED GROUP NUMBER 2										Item Number	
EXCITATION FREQUENCY GROUP 1										8.0	
HZ 92.8000 95.1234 97.5049 99.9461 102.4484 105.0134 107.6425 110.3375 113.1000										9.0	
END DETERMINANTS										11.0	
CO-ROTATIONAL CTR-ROTATIONAL											
1.679913E 14 3.423157E 13											
1.155819E 14 -1.025850E 13											
6.246683E 13 -5.473874E 13											
8.797742E 12 -9.904060E 13											
-4.525121E 13 -1.429772E 14											
-9.958163E 13 -1.863424E 14											
-1.536690E 14 -2.289098E 14											
-2.075608E 14 -2.704320E 14											
-2.608747E 14 -3.106400E 14										12.0	
TORSIONAL											
END STIFF											
-3.243267D 06											
-3.383256D 06											
-3.527914D 06											
-3.677243D 06											
-3.831224D 06											
-3.989812D 06											
-4.152936D 06											
-4.320494D 06										9.0	
-4.492347D 06											
EXCITATION FREQUENCY GROUP 2											
HZ 200.0000 311.7870 324.0370 336.7684 350.0000											11.0
END DETERMINANTS											
CO-ROTATIONAL CTR-ROTATIONAL											
1.004226E 15 4.205831E 13											
4.230628E 14 -5.598046E 14											
-5.051822E 14 -1.395417E 15											
-1.865942E 15 -2.495496E 15											
-3.749671E 15 -3.881267E 15											
TORSIONAL											
END STIFF											
-3.214928D 06										12.0	
-1.803141D 06											
-1.982565D 05											
1.591056D 06											
3.546048D 06											
BRC NO											13.0
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In order to gain some additional insight of the bending modes in preparation for subsequent analyses, a second asynchronous resonance analysis was dedicated to the bending modes of the two lower frequency ranges, this time invoking Level II analysis to obtain the mode shapes. Level II output of the second asynchronous resonance analysis is given in Table 17. In the first frequency range, resonances are found at 68.6 Hz and 67.5 Hz, respectively, for the co-rotational and counter-rotational modes. The relative frequency relationship is due to the effect of gyroscopic inertia. The amplitude distributions of these two modes are practically the same. It should be recalled that the relatively low bearing stiffness values assigned to this frequency range is an attempt to emulate the "half-speed" behavior of a fluid film bearing. Since the reduced effective bearing stiffness at "half-speed" is associated only with the co-rotational motion, the counter-rotational mode found in this frequency range should be disregarded for the present study. In the second frequency range, again a co-rotational mode and a counter-rotational mode are found, respectively, at 100.3 Hz and 94.6 Hz. Amplitude distributions of these modes are again very similar to each other. In comparison with the 68.6 Hz mode, the amplitudes at the bearing supports, stations 2 and 29, are much reduced at the higher frequency modes.

3.4.4 Asynchronous Response (IRUN = 4)

The example for damped asynchronous response was calculated with the same speed-frequency combinations used in the previous example; consequently, the input was set up to access the pre-stored intermediate data file in lieu of repeating Level I analysis. The complete output of the example is shown in Table 18.

Excitation is specified to be the space-fixed type. For the first frequency range a unit excitation force, aimed in the direction of the static load, is assigned at station 18, which is near the mid-span of the rotor and is the peak deflection point of the undamped co-rotational mode in Table 17. For the second frequency range, the excitation force is shifted to station 29, which is a bearing support where deflection is minimal for both undamped modes in this frequency range.

TABLE 17

COMPUTER OUTPUT OF ASYNCHRONOUS BENDING RESONANCE ANALYSIS

LEVEL II RESULTS

(From Input Data of Table 8)

7 Sheets

LUND ROTOR ASYNCHRONOUS BENDING ANALYSIS				Item Number
SHAFT SEGMENTS	=	32		
SHAFT MATERIALS	=	1		
LUMPED INERTIA STATIONS	=	18		
BEARINGS	=	2		1.0

TABLE 17 (CONT.)

*****CALCULATION SUMMARY*****			Item Number
TEST IRUN=3, 4.5 LUND ROTOR ASYNCHRONOUS BENDING ANALYSIS			14.0
ASYNCHRONOUS RESONANCE CALCULATION			
BENDING EXCITATION STATIONS			
2	11	18 29	

SHEET 2 OF 7

TABLE 17 (CONT.)

Item Number

LEVEL 2 BEARING DATA									
ROTATIONAL SPEED = 8 0000E 03 RPM FREQUENCY = 6 3000E 01 HZ									
BEARING NO. STM	TYPE	XX	YY	XY	YX	YY	YY	YY	YY
1 2	*	1 2950E 05 0 0000E-01	0 0000E-01	0 0000E-01	0 0000E-01	0 0000E-01	0 0000E-01	0 0000E-01	0 0000E-01
2 29	*	1 5350E 05 0 0000E-01	0 0000E-01	0 0000E-01	0 0000E-01	0 0000E-01	0 0000E-01	0 0000E-01	0 0000E-01
LEVEL 2 BEARING DATA									
ROTATIONAL SPEED = 8 0000E 03 RPM FREQUENCY = 5 4540E 01 HZ									
BEARING NO. STM	TYPE	XX	YY	XY	YX	YY	YY	YY	YY
1 2	*	1 2950E 05 0 0000E-01	0 0000E-01	0 0000E-01	0 0000E-01	0 0000E-01	0 0000E-01	0 0000E-01	0 0000E-01
2 29	*	1 5350E 05 0 0000E-01	0 0000E-01	0 0000E-01	0 0000E-01	0 0000E-01	0 0000E-01	0 0000E-01	0 0000E-01
LEVEL 2 BEARING DATA									
ROTATIONAL SPEED = 8 0000E 03 RPM FREQUENCY = 6 6322E 01 HZ									
BEARING NO. STM	TYPE	XX	YY	XY	YX	YY	YY	YY	YY
1 2	*	1 2950E 05 0 0000E-01	0 0000E-01	0 0000E-01	0 0000E-01	0 0000E-01	0 0000E-01	0 0000E-01	0 0000E-01
2 29	*	1 5350E 05 0 0000E-01	0 0000E-01	0 0000E-01	0 0000E-01	0 0000E-01	0 0000E-01	0 0000E-01	0 0000E-01
LEVEL 2 BEARING DATA									
ROTATIONAL SPEED = 8 0000E 03 RPM FREQUENCY = 6 8048E 01 HZ									
BEARING NO. STM	TYPE	XX	YY	XY	YX	YY	YY	YY	YY
1 2	*	1 2950E 05 0 0000E-01	0 0000E-01	0 0000E-01	0 0000E-01	0 0000E-01	0 0000E-01	0 0000E-01	0 0000E-01
2 29	*	1 5350E 05 0 0000E-01	0 0000E-01	0 0000E-01	0 0000E-01	0 0000E-01	0 0000E-01	0 0000E-01	0 0000E-01
LEVEL 2 BEARING DATA									
ROTATIONAL SPEED = 8 0000E 03 RPM FREQUENCY = 6 9819E 01 HZ									
BEARING NO. STM	TYPE	XX	YY	XY	YX	YY	YY	YY	YY
1 2	*	1 2950E 05 0 0000E-01	0 0000E-01	0 0000E-01	0 0000E-01	0 0000E-01	0 0000E-01	0 0000E-01	0 0000E-01
2 29	*	1 5350E 05 0 0000E-01	0 0000E-01	0 0000E-01	0 0000E-01	0 0000E-01	0 0000E-01	0 0000E-01	0 0000E-01
LEVEL 2 BEARING DATA									
ROTATIONAL SPEED = 8 0000E 03 RPM FREQUENCY = 7 1636E 01 HZ									
BEARING NO. STM	TYPE	XX	YY	XY	YX	YY	YY	YY	YY
1 2	*	1 2950E 05 0 0000E-01	0 0000E-01	0 0000E-01	0 0000E-01	0 0000E-01	0 0000E-01	0 0000E-01	0 0000E-01
2 29	*	1 5350E 05 0 0000E-01	0 0000E-01	0 0000E-01	0 0000E-01	0 0000E-01	0 0000E-01	0 0000E-01	0 0000E-01
LEVEL 2 BEARING DATA									
ROTATIONAL SPEED = 8 0000E 03 RPM FREQUENCY = 7 3500E 01 HZ									
BEARING NO. STM	TYPE	XX	YY	XY	YX	YY	YY	YY	YY
1 2	*	1 2950E 05 0 0000E-01	0 0000E-01	0 0000E-01	0 0000E-01	0 0000E-01	0 0000E-01	0 0000E-01	0 0000E-01
2 29	*	1 5350E 05 0 0000E-01	0 0000E-01	0 0000E-01	0 0000E-01	0 0000E-01	0 0000E-01	0 0000E-01	0 0000E-01

16.2

TABLE 17 (CONT.)

UNDAMPED ASYNCHRONOUS STIFFNESS DETERMINANTS									
ROTATIONAL SPEED = 8.0000E 03 RPM									
FREQUENCY		***** DETERMINANTS *****							
(HZ)	CO -ROT	CTR-ROT							
6.3080E 01	2.8755E 00	1.9106E 00							
6.4640E 01	1.6326E 00	9.6797E-01							
6.6322E 01	7.5063E-01	3.1663E-01							
6.8048E 01	1.4110E-01	-1.1774E-01							
6.9819E 01	-2.6473E-01	-3.9241E-01							
7.1636E 01	-5.1994E-01	-5.5120E-01							
7.3500E 01	-6.6537E-01	-6.2748E-01							
CO-ROTATIONAL MODE									
	FREQ (HZ)	LOCATION (IN)	DEFLECTION	SLOPE					
	6.8621E 01	3.149E 00	6.2909E-01						
		1.3539E 01	9.4850E-01						
		2.1567E 01	1.0000E 00						
		3.7855E 01	5.2192E-01						
NO OF CO-ROTATIONAL ROOTS = 1									
CTR-ROTATIONAL MODE									
	FREQ (HZ)	LOCATION (IN)	DEFLECTION	SLOPE					
	6.7536E 01	3.149E 00	6.2607E-01						
		1.3539E 01	9.5105E-01						
		2.1567E 01	1.0000E 00						
		3.7855E 01	5.0063E-01						
NO OF CTR-ROTATIONAL ROOTS = 1									
				20.0					

TABLE 17 (CONT.)

Item Number	
*****CALCULATION SUMMARY***** TEST IRUM=3,4,5 LUNG ROTOR ASYNCHRONOUS BENDING ANALYSIS ASYNCHRONOUS RESONANCE CALCULATION BENDING EXCITATION STATIONS 2 11 18 29	14.0

TABLE 17 (CONT)

LEVEL 2 BEARING DATA										Item Number									
ROTATIONAL SPEED = 8 0000E 03 RPM										FREQUENCY = 9 2600E 01 HZ									
BEARING TYPE										K									
NO. STM										K									
RADIAL ANGULAR										K									
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
2	29	28	27	26	25	24	23	22	21	20	19	18	17	16	15	14	13	12	11
LEVEL 2 BEARING DATA										FREQUENCY = 9 5127E 01 HZ									
ROTATIONAL SPEED = 8 0000E 03 RPM										FREQUENCY = 9 5127E 01 HZ									
BEARING TYPE										K									
NO. STM										K									
RADIAL ANGULAR										K									
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
2	29	28	27	26	25	24	23	22	21	20	19	18	17	16	15	14	13	12	11
LEVEL 2 BEARING DATA										FREQUENCY = 9 7505E 01 HZ									
ROTATIONAL SPEED = 8 0000E 03 RPM										FREQUENCY = 9 7505E 01 HZ									
BEARING TYPE										K									
NO. STM										K									
RADIAL ANGULAR										K									
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
2	29	28	27	26	25	24	23	22	21	20	19	18	17	16	15	14	13	12	11
LEVEL 2 BEARING DATA										FREQUENCY = 9 9546E 01 HZ									
ROTATIONAL SPEED = 8 0000E 03 RPM										FREQUENCY = 9 9546E 01 HZ									
BEARING TYPE										K									
NO. STM										K									
RADIAL ANGULAR										K									
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
2	29	28	27	26	25	24	23	22	21	20	19	18	17	16	15	14	13	12	11
LEVEL 2 BEARING DATA										FREQUENCY = 1 0245E 02 HZ									
ROTATIONAL SPEED = 8 0000E 03 RPM										FREQUENCY = 1 0245E 02 HZ									
BEARING TYPE										K									
NO. STM										K									
RADIAL ANGULAR										K									
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
2	29	28	27	26	25	24	23	22	21	20	19	18	17	16	15	14	13	12	11
LEVEL 2 BEARING DATA										FREQUENCY = 1 0501E 02 HZ									
ROTATIONAL SPEED = 8 0000E 03 RPM										FREQUENCY = 1 0501E 02 HZ									
BEARING TYPE										K									
NO. STM										K									
RADIAL ANGULAR										K									
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
2	29	28	27	26	25	24	23	22	21	20	19	18	17	16	15	14	13	12	11
LEVEL 2 BEARING DATA										FREQUENCY = 1 0764E 02 HZ									
ROTATIONAL SPEED = 8 0000E 03 RPM										FREQUENCY = 1 0764E 02 HZ									
BEARING TYPE										K									
NO. STM										K									
RADIAL ANGULAR										K									
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
2	29	28	27	26	25	24	23	22	21	20	19	18	17	16	15	14	13	12	11
LEVEL 2 BEARING DATA										FREQUENCY = 1 1034E 02 HZ									
ROTATIONAL SPEED = 8 0000E 03 RPM										FREQUENCY = 1 1034E 02 HZ									
BEARING TYPE										K									
NO. STM										K									
RADIAL ANGULAR										K									
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
2	29	28	27	26	25	24	23	22	21	20	19	18	17	16	15	14	13	12	11
LEVEL 2 BEARING DATA										FREQUENCY = 1 1210E 02 HZ									
ROTATIONAL SPEED = 8 0000E 03 RPM										FREQUENCY = 1 1210E 02 HZ									
BEARING TYPE										K									
NO. STM										K									
RADIAL ANGULAR										K									
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
2	29	28	27	26	25	24	23	22	21	20	19	18	17	16	15	14	13	12	11

16.0

TABLE 17 (CONT.)

Item Number					
UNDAMPED ASYNCHRONOUS STIFFNESS DETERMINANTS					
ROTATIONAL SPEED = 8.0000E 03 RPM					
***** DETERMINANTS *****					
CO - ROT CTR-ROT					
FREQUENCY (HZ)	CO - ROT	CTR-ROT			
9.2800E 01	9.4961E 00	2.1743E 00			
9.5123E 01	5.4109E 00	-5.4145E-01			
9.7505E 01	2.4233E 00	-2.4025E 00			
9.9946E 01	2.8299E-01	-3.6174E 00			
1.0245E 02	-1.2077E 00	-4.3494E 00			
1.0501E 02	-2.2046E 00	-4.7252E 00			
1.0764E 02	-2.8298E 00	-4.8432E 00			
1.1034E 02	-3.1788E 00	-4.7788E 00			
1.1310E 02	-3.3257E 00	-4.5897E 00			
CO-ROTATIONAL MODE					
	FREQ (HZ)	LOCATION (IN)	DEFLECTION	SLOPE	
	1.0034E 02	3.1496E 00	1.5738E-01		
		1.3539E 01	8.5190E-01		
		2.1567E 01	1.0000E 00		
		3.7855E 01	8.9878E-02		
NO OF CO-ROTATIONAL ROOTS = 1					
CTR-ROTATIONAL MODE					
	FREQ (HZ)	LOCATION (IN)	DEFLECTION	SLOPE	
	9.4609E 01	3.1496E 00	1.3981E-01		
		1.3539E 01	8.4282E-01		
		2.1567E 01	1.0000E 00		
		3.7855E 01	7.7683E-02		
NO OF CTR-ROTATIONAL ROOTS = 1					
20.0					

TABLE 18

COMPUTER OUTPUT OF DAMPED ASYNCHRONOUS RESPONSE ANALYSIS
(From Input Data of Table 9)

25 Sheets

*****CALCULATION SUMMARY*****		Item Number	Remarks
TEST IRUN=3,4,5 LUND ROTOR ASYNCHRONOUS BENDING ANALYSIS			
ASYNCHRONOUS RESPONSE			
EXCITATION IS STATIONARY			
BENDING EXCITATION STATIONS			
2	11 16 29	14.0	Freq. Group No. 1

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TABLE 18 (CONT.)

LEVEL 2 BEARING DATA		FREQUENCY = 6 3000E 01 HZ		Item Number	Remarks
ROTATIONAL SPEED = 8.0000E 03 RPM				16.0	Freq. Point No. 1 of 7
BEARING TYPE	NO. STN	XX	YY		
RADIAL ANGULAR		K	K		
1 2	6 6956E 05 9 2412E 02 4 5395E 05 2 2607E 02 3 0312E 04 2 2607E 02 1 7531E 05 1 5177E 02				
2 29	8 9993E 05 1 1572E 03 5 6968E 05 2 7284E 02 4 9946E 04 2 7264E 02 2 1097E 05 1 7124E 02				
EXCITATION DATA					
NO. STN	TYPE	***** VERTICAL *****	***** HORIZONTAL *****		
1 2	FORCE	IN-PHASE	IN-PHASE		
2 11	MOMENT	LAG	LAG		
3 18		0.0000E-01 0 0000E-01 0 0000E-01 0 0000E-01	0.0000E-01 0 0000E-01 0 0000E-01		
4 29		1 0000E 00 0 0000E-01 0 0000E-01 0 0000E-01	1 0000E 00 0 0000E-01 0 0000E-01 0 0000E-01		
RESPONSE ORBIT					
ROTATIONAL SPEED = 8.0000E 03 RPM		FREQUENCY = 6 3000E 01 HZ		19.1	
NO. STN	LOCATION	DISPL	SLOPE	** PRINCIPAL RADII	** INCLINATION
1 2	3 1496	*	*	MAJOR MINOR	PHASE REFERENCE
2 11	13 5395	*	*	2 6178E-06-1 5643E-06 4 426E 00 7 8439E 01	ELLIPTICITY
3 18	21 5673	*	*	6 706E-06-2 7853E-06 3 930E 01 4 423E 01	2 5192E-01
4 29	37.8547	*	*	7 0586E-06-2 9171E-06 4 1539E 01 4 5691E 01	3 7800E-01
				2 0453E-06-1 3042E-06 -9 9503E-01 4 0772E 01	4 1516E-01
					2 2126E-01

TABLE 18 (CONT.)

LEVEL 2 BEARING DATA		FREQUENCY = 6 4540E 01 HZ		Item Number		Remarks	
ROTATIONAL SPEED = 8 0000E 03 RPM							
BEARING TYPE		K		16.0		Freq. Point No. 2 of 1	
NO. SYN RADIAL ANGULAR		K					
1	2	6 6956E 05	9 2412E 02	4 5345E 05	2 2607E 02	3 0312E 04	2 2607E 02
2	29	8 9993E 05	1 1572E 03	5 6548E 05	2 7264E 02	4 9946E 04	2 7264E 02
EXCITATION DATA							
TYPE		***** VERTICAL *****		***** HORIZONTAL *****			
NO SIN FORCE MOMENT		IN-PHASE LAG		IN-PHASE LAG			
1	2	0 0000E-01	0 0000E-01	0 0000E-01	0 0000E-01		
2	11	0 0000E-01	0 0000E-01	0 0000E-01	0 0000E-01		
3	18	1 0000E 00	0 0000E-01	0 0000E-01	0 0000E-01		
4	29	0 0000E-01	0 0000E-01	0 0000E-01	0 0000E-01		
RESPONSE ORBIT							
ROTATIONAL SPEED = 8 0000E 03 RPM		FREQUENCY = 6 4540E 01 HZ		19.1			
NO SIN LOCATION DISPL SLOPE		** PRINCIPAL RADII **		** INCLINATION **		PHASE REFERENCE	
1	2	3 3249E-06	-2 1898E-06	-7 9435E-01	5 0074E 01	ELLIPTICITY	
2	11	7 0643E-06	-4 0561E-06	4 6659E 01	5 0743E 01	2 1509E-01	
3	18	8 0044E-06	-4 5533E-06	4 3481E 01	5 0988E 01	2 7051E-01	
4	29	2 6737E-06	-1 7885E-06	-7 5031E 00	5 3163E 01	3 0596E-01	
						1 9838E-01	

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TABLE 18 (CONT.)

LEVEL 2 BEARING DATA										FREQUENCY = 6 6322E 01 HZ										Item Number										Remarks																																																											
ROTATIONAL SPEED = 8 0000E 03 RPM																																																																																									
BEARING										TYPE										XX										YY										VY										16.0																																							
NO. STN										RADIAL ANGULAR																																																																															
1										2										6 6956E 05 9 2412E 02 4 5395E 05 2 2607E 02 3 0312E 04 2 2607E 02 1.7531E 05 1 5177E 02																																																																					
2										29										8 9993E 05 1 1572E 03 5 6968E 05 2 7264E 02 4 9346E 04 2 7264E 02 2.1097E 05 1.7124E 02																																																																					
EXCITATION DATA																																																																																									
*** TYPE ***										*** VERTICAL ***										*** HORIZONTAL ***																																																																					
NO SIN										FORCE										MOMENT										IN-PHASE										LAG										IN-PHASE										LAG																													
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4										29										*										0 0000E-01 0 0000E-01 0 0000E-01 0 0000E-01																																																											
RESPONSE ORBIT																																																																																									
ROTATIONAL SPEED = 8.0000E 03 RPM																				FREQUENCY = 6 6322E 01 HZ																				19.1																																																	
NO. STN										LOCATION										DISPL										SLOPE										** PRINCIPAL RADII										** INCLINATION										PHASE																													
																																								MAJOR										MINOR										(DEG)										REFERENCE										ELLIPTICITY									
1										2										3 1496										*										4 7180E-06-3 2735E-06										-8 9652E 00 7 9685E 01																				1 8075E-01																			
2										11										13 5395										*										8 3055E-06-6 3203E-06										5 0100E 01 6 7998E 01																				1 3573E-01																			
3										18										21 5673										*										9 3374E-06-6 5829E-06										5 3881E 01 6 6896E 01																				1 7302E-01																			
4										29										37 8547										*										3 7795E-06-2 6037E-06										-1 6350E 01 8 3285E 01																				1 8328E-01																			

TABLE 18 (CONT.)

LEVEL 2 BEARING DATA		FREQUENCY = 6 8048E 01 HZ		Item Number	
ROTATIONAL SPEED = 8 0000E 03 RPM					
BEARING *** TYPE ***					
NO. STN	RADIAL ANGLE	XX	YY	XY	16.0
1 2	*	6 6956E 05 9 2412E 02 4 5395E 05 2 2607E 02 7 0312E 04 2 2607E 02 1 7531E 05 1 5177E 02			
2 29	*	8 9993E 05 1 1572E 03 5 4968E 05 3 7264E 02 4 9346E 04 2 7264E 02 2 1097E 05 1 7124E 02			
EXCITATION DATA					
*** TYPE ***					
NO. STN	FORCE	MOMENT	IN-PHASE	LAG	HORIZONTAL
1 2	*	0 0000E-01 0 0000E-01 0 0000E-01 0 0000E-01 0 0000E-01			
2 11	*	0 0000E-01 0 0000E-01 0 0000E-01 0 0000E-01 0 0000E-01			
3 18	*	1 0000E 00 0 0000E-01 0 0000E-01 0 0000E-01 0 0000E-01			
4 29	*	0 0000E-01 0 0000E-01 0 0000E-01 0 0000E-01 0 0000E-01			
RESPONSE ORBIT					
ROTATIONAL SPEED = 8 0000E 03 RPM		FREQUENCY = 6 8048E 01 HZ		19.1	
NO STN	LOCATION	DISPL	SLOPE	** PRINCIPAL RADII	** INCLINATION
1 2	3 1496	*		MAJOR MINOR (DEG)	PHASE REFERENCE
2 11	13 5395	*		5 7556E-06-4 1589E-06 -2 1772E 01 1 275F 02	ELLIPTICITY
3 18	21 5673	*		9 4813E-06-6 9299E-06 -8 3064E 01 1 0431E 02	1 6106E-01
4 29	37 6547	*		1 0533E-05-7 0766E-06 -8 7689E 01 1 0083E 02	1 5346E-01
				4 7002E-06-3 2327E-06 -2 7389E 01 1 2318E 02	1 9629E-01
					1 8498E-01

TABLE 18 (CONT.)

LEVEL 2 BEARING DATA										Item Number	Remarks
ROTATIONAL SPEED = 8.0000E 03 RPM FREQUENCY = 6 9819E 01 HZ											
BEARING NO. STN	TYPE	XX	YY	K	XY	K	YK	K	YY	16.0	
RADIAL ANGULAR											
1	2	6 6956E 05 9.2412E 02	4 5395E 05 2 2607E 02	3 0312E 04	2 2607E 02	1.7531E 05	1.5177E 02				
2	29	8 9933E 05 1 1572E 03	5 6968E 05 2 7264E 02	4 9946E 04	2 7264E 02	2.1097E 05	1.7124E 02			19.1	
EXCITATION DATA											
**** TYPE ****											
***** VERTICAL *****											
***** HORIZONTAL *****											
NO STN	FORCE	IN-PHASE	LAG	IN-PHASE	LAG						
1	2	0.0000E-01	0.0000E-01	0.0000E-01	0.0000E-01						
2	11	0.0000E-01	0.0000E-01	0.0000E-01	0.0000E-01						
3	18	1.0000E 00	0.0000E-01	0.0000E-01	0.0000E-01						
4	29	0.0000E-01	0.0000E-01	0.0000E-01	0.0000E-01						
RESPONSE ORBIT										19.1	
ROTATIONAL SPEED = 8.0000E 03 RPM FREQUENCY = 6 9819E 01 HZ											
NO STN	LOCATION	DISPL	SLOPE	** PRINCIPAL RADII	** INCLINATION	PHASE					
				MAJOR MINOR	(DEG)	REFERENCE					
1	2	7.1496	*	4 2657E-06-2 9735E-06	-3 7733E 01	1 5312E 02					
2	11	13.5395	*	7 8418E-06-2 8614E-06	-7 5037E 01	1 1812E 02					
3	18	21.5673	*	8.7060E-06-2 6423E-06	-7 3469E 01	1.1232E 02					
4	29	37.8547	*	3.5232E-06-2 2849E-06	-3 8796E 01	1.5208E 02					
						2.1319E-01					

TABLE 18 (CONT.)

LEVEL 2 BEARING DATA										Item Number	Remarks
BEARING NO. STM TYPE XXXX FREQUENCY = 7 1636E 01 HZ											
ROTATIONAL SPEED = 8 0000E 03 RPM											
K K											

TABLE 18 (CONT.)

LEVEL 2 BEARING DATA															Item Number	Remarks
ROTATIONAL SPEED = 8.0000E 03 RPM FREQUENCY = 7 3500E 01 HZ																
BEARING TYPE																
NO. STM RADIAL ANGULAR																
1	2	*	6 6956E 05	9 2412E 02	4 5395E 05	2 2607E 02	3 0312E 04	2 2607E 02	1 7531E 05	1 5177E 02			16.0	Freq. Point No. 7 of 7		
2	29	*	8 9993E 05	1 1572E 03	5 6968E 05	2 7264E 02	4 9946E 04	2 7264E 02	2 1097E 05	1 7124E 02						
EXCITATION DATA																
***** VERTICAL ***** ***** HORIZONTAL *****																
NO. STM FORCE MOMENT																
1	2	*	0 0000E-01	0 0000E-01	0 0000E-01	0 0000E-01	0 0000E-01	0 0000E-01	0 0000E-01	0 0000E-01						
2	11	*	0 0000E-01	0 0000E-01	0 0000E-01	0 0000E-01	0 0000E-01	0 0000E-01	0 0000E-01	0 0000E-01						
3	18	*	1 0000E 00	0 0000E-01	0 0000E-01	0 0000E-01	0 0000E-01	0 0000E-01	0 0000E-01	0 0000E-01						
4	29	*	0 0000E-01	0 0000E-01	0 0000E-01	0 0000E-01	0 0000E-01	0 0000E-01	0 0000E-01	0 0000E-01						
RESPONSE ORBIT																
ROTATIONAL SPEED = 8.0000E 03 RPM FREQUENCY = 7 3500E 01 HZ															19.1	
***** PRINCIPAL RADII ***** ***** INCLINATION *****																
NO. STM LOCATION DISPL SLOPE																
1	2	*	2.1193E-06	-9 8326E-07	-5 9842E 01	1 6218E 02										
2	11	*	5.1027E-06	1.0871E-06	-8 8506E 01	8 1504E 01										
3	18	*	5.9637E-06	1 4509E-06	8 6572E 01	7 6998E 01										
4	29	*	1.7219E-06	-7 9500E-07	-5 5973E 01	1 6207E 02										
ELLIPTICITY																
3 6617E-01																
6.4874E-01																
6 0863E-01																
3 6610E-01																

TABLE 18 (CONT.)

Item Number										Remarks
I	FREQ	DAMP	MODAL MASS	DAMP RATIO	F-CHANGE	C-CHANGE	PESIQUE	CHECK	Mode No. 1	
1	6.8110 01	1 3570 00	3 3230-01	2.9980-02	4 6750-04	2 6310-04	1 9130-03	-3 6670-02		
2	6.8110 01	1 3570 00	3 3220-01	2.9990-02	4 4360-08	3 2350-08	2 5960-11	-3 6720-02	21.2	

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TABLE 18 (CONT.)

I	FREQ	DAMP	MODAL MASS	DAMP RATIO	F-CHANGE	C-CHANGE	RESIDUE	D CHECK	Item Number		Remarks
1	6.8110 01	1 3570 00	2.5620-02	3 8880-01	1 7690-02	5 2760-04	1 8330 03	-4 3800-01	21.2	Mode No. 2	
2	6.8130 01	1 3570 00	2.5690-02	3 8770-01	-3 0500-04	4 6120-04	4 7880 02	-4 2670-01			
3	6.8130 01	1 3580 00	2.5690-02	3 8790-01	-2 9770-04	4 0860-04	3 7680 02	-4 2710-01			
4	6.8130 01	1 3580 00	2.5680-02	3 8790-01	-2 6390-04	3 6190-04	2 9550 02	-4 2710-01			
5	6.8130 01	1 3590 00	2.5680-02	3 8830-01	-2 3390-04	3 2050-04	2 3180 02	-4 2790-01			
6	6.8130 01	1 3590 00	2.5670-02	3 8850-01	-2 0720-04	2 8350-04	1 8180 02	-4 2820-01			
7	6.8130 01	1 3590 00	2.5670-02	3 8860-01	-1 8360-04	2 5150-04	1 4260 02	-4 2850-01			
8	6.8130 01	1 3600 00	2.5670-02	3 8870-01	-1 6270-04	2 2270-04	1 1180 02	-4 2870-01			
9	6.8130 01	1 3600 00	2.5660-02	3 8890-01	-1 4410-04	1 9730-04	8 7730 01	-4 2890-01			
10	6.8130 01	1 3600 00	2.5660-02	3 8900-01	-1 2770-04	1 7470-04	6 8810 01	-4 2910-01			
11	6.8130 01	1 3600 00	2.5660-02	3 8900-01	-1 1310-04	1 5480-04	5 3970 01	-4 2930-01			
12	6.8130 01	1 3600 00	2.5660-02	3 8910-01	-1 0020-04	1 3710-04	4 2330 01	-4 2940-01			
13	6.8130 01	1 3610 00	2.5650-02	3 8910-01	-8 8790-05	1 2140-04	3 3210 01	-4 2940-01			
14	6.8130 01	1 3610 00	2.5650-02	3 8920-01	-7 8650-05	1 0750-04	2 6050 01	-4 2970-01			
15	6.8130 01	1 3610 00	2.5650-02	3 8920-01	-6 7670-05	9 5240-05	2 0430 01	-4 2970-01			
16	6.8130 01	1 3610 00	2.5650-02	3 8930-01	-6 1720-05	8 4350-05	1 6020 01	-4 2990-01			
17	6.8130 01	1 3610 00	2.5650-02	3 8940-01	-5 4670-05	7 4710-05	1 2570 01	-4 3000-01			
18	6.8130 01	1 3610 00	2.5650-02	3 8940-01	-4 8420-05	6 6170-05	9 8590 00	-4 3010-01			
19	6.8130 01	1 3610 00	2.5650-02	3 8950-01	-4 2890-05	5 8600-05	7 7340 00	-4 3010-01			
20	6.8130 01	1 3610 00	2.5650-02	3 8950-01	-3 7990-05	5 1900-05	6 0660 00	-4 3020-01			

TABLE 18 (CONT.)

ROTATIONAL SPEED = 8 000E 03 PPM FREQUENCY = 6 8114E 01 HZ CRIT DAMP RATIO = 2 9986E-02 PRECISION INDEX = -3 6718E-02 NATURAL MODE SHAPE									
** PRINCIPAL RADII ** INCLINATION PHASE MAJOR MINOR (DEG) REFERENCE ELLIPTICITY									
NO	STN	LOCATION	DISPL	SLOPE					
1	2	3	1496	*	1 1335E 00	2 0729E-01	-5 5521E 01-4	-5 5521E 01	6 9080E-01
2	11	13	5395	*	1 6911E 00	2 3654E-01	-5 6117E 01-4	-5 6117E 01	7 5458E-01
3	18	21	5673	*	1 7703E 00	2 2968E-01	-5 6353E 01-4	-5 6353E 01	7 7032E-01
4	29	37	8547	*	9 0723E-01	1 5079E-01	-5 2265E 01-4	-5 2265E 01	7 1496E-01
RESONANT RESPONSE:									
EXCITATION DATA									
*** TYPE *** NO STN LOCATION DISPL SLOPE FORCE MOMENT									
***** VERTICAL ***** IN-PHASE LAG IN-PHASE LAG									
1	2	*			0 0000E-01	0 0000E-01	0 0000E-01	0 0000E-01	
2	11	*			0 0000E-01	0 0000E-01	0 0000E-01	0 0000E-01	
3	18	*			1 0000E 00	0 0000E-01	0 0000E-01	0 0000E-01	
4	29	*			0 0000E-01	0 0000E-01	0 0000E-01	0 0000E-01	
*** HORIZONTAL *** IN-PHASE LAG IN-PHASE LAG									
1	2	*			0 0000E-01	0 0000E-01	0 0000E-01	0 0000E-01	
2	11	*			0 0000E-01	0 0000E-01	0 0000E-01	0 0000E-01	
3	18	*			1 0000E 00	0 0000E-01	0 0000E-01	0 0000E-01	
4	29	*			0 0000E-01	0 0000E-01	0 0000E-01	0 0000E-01	
RESPONSE ORBIT									
** PRINCIPAL RADII ** INCLINATION PHASE MAJOR MINOR (DEG) REFERENCE ELLIPTICITY									
NO	STN	LOCATION	DISPL	SLOPE					
1	2	3	1496	*	2 1235E-04	3 8641E-05	-5 5217E 01-6	-5 5217E 01	6 9197E-01
2	11	13	5395	*	3 1892E-04	4 1284E-05	-5 5200E 01-5	-5 5200E 01	7 7078E-01
3	18	21	5673	*	3 3433E-04	3 9296E-05	-5 5310E 01-5	-5 5310E 01	7 8965E-01
4	29	37	8547	*	1 6985E-04	2 3095E-05	-5 6937E 01-6	-5 6937E 01	7 1614E-01

TABLE 18 (CONT.)

Item Number	Remarks
14.0	Freq. Group No. 2

*****CALCULATION SUMMARY*****
 TEST IRUN=3, 4, 5 LUND ROTOR ASYNCHRONOUS BENDING ANALYSIS
 ASYNCHRONOUS RESPONSE
 EXCITATION IS STATIONARY
 BENDING EXCITATION STATIONS
 2 11 18 29

TABLE 18 (CONT.)

LEVEL 2 BEARING DATA		FREQUENCY = 9 2800E 01 HZ		Item Number	Remarks
ROTATIONAL SPEED = 8 0000E 03 RPM				16.0	Freq. Point No. 1 of 9
BEARING	TYPE	XX	XY		
NO. STN	RADIAL ANGULAR				
1	2	6 6956E 05 9 2412E 02 4 5395E 05 2 2607E 02 3 0312E 04 2 2607E 02 1 7531E 05 1.5177E 02			
2	29	8 9993E 05 1 1572E 03 5 6968E 05 2 7264E 02 4 9946E 04 2 7264E 02 2.1097E 05 1 7124E 02			
EXCITATION DATA					
NO	STN	FORCE	MOMENT		
1	2				
2	11				
3	18				
4	29				
RESPONSE ORBIT					
ROTATIONAL SPEED = 8 0000E 03 RPM		FREQUENCY = 9 2800E 01 HZ		19.1	
NO	STN	LOCUTION	DISPL	SLOPE	
1	1	3 1.96	*		
2	11	13 5.95	*		
3	18	21 5.73	*		
4	29	37 8.47	*		

TABLE 18 (CONT.)

LEVEL 2 SCARING DATA		FREQUENCY = 9 5123E 01 HZ		Item Number	Remarks
ROTATIONAL SPEED = 8 0000E 03 RPM				16.0	Freq. Point No. 2 of 9
BEARING TYPE		***** XX ***** K ***** XY ***** K ***** YX ***** K ***** YY *****			
NO. STN		6 6950E 05 9 2412E 02 4 3395E 05 2 2607E 02 3 0312E 04 2 2607E 02 1 7531E 05 1 5177E 02			
1 2 *		8 9993E 05 1 1572E 03 5 6968E 05 2 7264E 02 4 9346E 04 2 7264E 02 2 1097E 05 1 7124E 02			
2 29 *					
EXCITATION DATA				19.1	
***** TYPE *****		***** VERTICAL ***** *** HORIZONTAL ***			
NO STN		IN-PHASE LAG IN-PHASE LAG			
1 2 *		0 0000E-01 0 0000E-01 0 0000E-01 0 0000E-01			
2 11 *		0 0000E-01 0 0000E-01 0 0000E-01 0 0000E-01			
3 18 *		0 0000E-01 0 0000E-01 0 0000E-01 0 0000E-01			
4 29 *		1 0000E 00 0 0000E-01 9 0026E-01 0 0 00E-01			
RESPONSE ORBIT					
ROTATIONAL SPEED = 8 0000E 03 RPM		FREQUENCY = 9 5123E 01 HZ			
NO STN		** PRINCIPAL RADII ** INCLINATION PHASE			
1 2 *		MAJOR MINOR (DEG) REFERENCE ELLIPTICITY			
2 11 *		9 3254E-07-7 5038E-07 -6 9342E 01-1 2224E 02			
3 18 *		2 5096E-06 1 1653E-08 6 7558E 01-1 1153E 02			
4 29 *		1 8222E-06-8 7550E-07 8 7613E-01 5 5606E 01			

TABLE 18 (CONT.)

Item Number		Remarks	
LEVEL 2 BEARING DATA			
ROTATIONAL SPEED = 3 0000E 03 RPM FREQUENCY = 9 7505E 01 HZ			
BEARING NO. STN TYPE ANGULAR XX YY XY YX YZ Freq. Point No. 3 of 9			
1 2 * 6 6356E 05 9 2412E 02 4 5395E 05 2 2607E 02 3 0313E 04 2 2607E 02 1 7531E 05 1 5177E 02			
2 29 * 8 9933E 05 1 1573E 03 5 6968E 05 2 7234E 02 3 3945E 04 2 7364E 02 2 1097E 05 1 7124E 02			
EXCITATION DATA			
*** TYPE *** *** VERTICAL *** *** HORIZONTAL ***			
NO STN FORCE MOMENT IN-PHASE LAC IN-PHASE LAC			
1 2 * 0 0000E-01 0 0000E-01 0 0000E-01 0 0000E-01			
2 11 * 0 0000E-01 0 0000E-01 0 0000E-01 0 0000E-01			
3 18 * 0 0000E-01 0 0000E-01 0 0000E-01 0 0000E-01			
4 29 * 1 0000E 00 0 0000E-01 0 0000E-01 0 0000E-01			
RESPONSE ORBIT			
ROTATIONAL SPEED = 3 0000E 03 RPM FREQUENCY = 9 7505E 01 HZ			
19.1			

TABLE 18 (CONT.)

LEVEL 2 BEARING DATA		FREQUENCY = 9.9946E 01 HZ		Item Number		Remarks	
ROTATIONAL SPEED = 8.0000E 03 RPM							
BEARING TYPE		K					
NO. STN		K					
1 2		6.6956E 05 9.2412E 02 4.5395E 05 2.2807E 02 3.0312E 04 2.2607E 02 1.7531E 05 1.5177E 02					
2 29		8.9993E 05 1.1572E 03 5.6968E 05 2.7364E 02 4.9946E 04 2.7264E 02 2.1097E 05 1.7124E 02					
EXCITATION DATA							
NO STN		K					
1 2		0.0000E-01 0.0000E-01 0.0000E-01 0.0000E-01 0.0000E-01					
2 11		0.0000E-01 0.0000E-01 0.0000E-01 0.0000E-01 0.0000E-01					
3 18		0.0000E-01 0.0000E-01 0.0000E-01 0.0000E-01 0.0000E-01					
4 29		1.0000E 00 0.0000E-01 0.0000E-01 0.0000E-01 0.0000E-01					
RESPONSE ORBIT							
ROTATIONAL SPEED = 8.0000E 03 RPM		FREQUENCY = 9.9946E 01 HZ					
NO STN		K					
1 2		1.2906E-06-8.2420E-07 6.7994E 00-1.1508E 01					
2 11		2.8061E-06-4.3374E-07 5.0806E 01-1.5289E 04					
3 18		2.9898E-06 1.5474E-07 4.6615E 01-1.3299E 02					
4 29		1.5069E-06-1.1029E-06 -1.6004E 01 9.2867E 01					

TABLE 18 (CONT.)

LEVEL 2 BEARING DATA										Item Number	Remarks
ROTATIONAL SPEED = 8 0000E 03 RPM FREQUENCY = 1 0345E 02 RZ										16.0	Freq. Point No. 5 of 9
BEARING TYPE *****											
NO. SYN RADIAL ANGULAR											
1 2 6 955E 05 9 2412E 02 4 5345E 04 2 2607E 02 3 0312E 04 2 2607E 02 1 7531E 05 1 5177E 02											
2 29 8 9900E 05 1 1500E 03 5 8903E 05 2 7264E 04 4 9946E 04 2 7264E 02 2 1037E 05 1 7124E 02											
EXCITATION DATA											
***** VERTICAL ***** ***** HORIZONTAL *****											
NO STN FORCE MOMENT IN-PHASE LAG IN-PHASE LAG											
1 2 0 0000E-01 0 0000E-01 0 0000E-01 0 0000E-01 0 0000E-01											
2 11 0 0000E-01 0 0000E-01 0 0000E-01 0 0000E-01 0 0000E-01											
3 18 0 0000E-01 0 0000E-01 0 0000E-01 0 0000E-01 0 0000E-01											
4 29 1 0000E 00 0 0000E-01 0 0000E-01 0 0000E-01 0 0000E-01											
RESPONSE ORBIT											
ROTATIONAL SPEED = 8 0000E 03 RPM FREQUENCY = 1 0345E 02 RZ										19.1	
***** TYPE *****											
NO STN LOCATION DISPL SLOPE ** PRINCIPAL RADII ** INCLINATION PHASE											
NO STN LOCATION DISPL SLOPE MAJOR MINOR (DEG) REFERENCE ELLIPTICITY											
1 2 3 1496 * 1 3431E-06-7 9524E-07 -6 2136E 00-9 2227E 01 2 5622E-01											
2 11 17 5395 * 1 9939E-06-5 6788E-07 4 6202E 01-1 2707E 02 5 5622E-01											
3 18 21 5673 * 1 9408E-06-5 2465E-08 4 2481E 01-1 3793E 02 9 4736E-01											
4 29 37 8547 * 1 9782E-06-1 3348E-06 -1 8512E 01 1 0128E 02 1 9421E-01											

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TABLE 18 (CONT.)

LEVEL 2 BEARING DATA		FREQUENCY = 1 0501E 02 HZ		Item Number	Remarks
ROTATIONAL SPEED = 8 0000E 03 RPM				16.0	Freq. Point No. 6 of 9
BEARING	TYPE	XX	XY	YX	YY
NO. STN	RADIAL ANGULAR	K	K	K	K
1 2	*	6 6956E 05 9 2412E 02 4 5395E 05 2 2607E 02 3 0312E 04 2 2607E 02 1.7531E 05 1.5177E 02			
2 29	*	8 9933E 05 1 1572E 03 5 6968E 05 2 7264E 02 4 9946E 04 2 7264E 02 2.1097E 05 1.7124E 02			
EXCITATION DATA					
*** I / PE ***					
***** VERTICAL *****					
NO	STN	FORCE	MOMENT	IN-PHASE	LAG
1	2	*		0 0000E-01	0 0000E-01
2	11	*		0 0039E-01	0 0000E-01
3	18	*		0 0000E-01	0 0000E-01
4	29	*		1 0000E 00	0 0000E-01
***** HORIZONTAL *****					
*** RESPONSE ORBIT ***					
ROTATIONAL SPEED = 8 0000E 03 RPM					
FREQUENCY = 1 0501E 02 HZ					
NO	STN	LOCATION	DISPL	SLOPE	PHASE
1	2	3 1496	*	1 3434E-06-7 8087E-07	-1 2356E 01-6 379E 01
2	11	13.5395	*	1 4916E-06-6 2152E-07	4 4883E 01-1 1827E 02
3	18	21.5673	*	1 3397E-06 6 3160E-09	3 8757E 01 1 4135E 02
4	29	77.8547	*	2.0634E-06-1 4480E-06	-2 2064E 01 1 1216E 02
19.1					

TABLE 18 (CONT.)

LEVEL 2 BEARING DATA		Item Number		Remarks	
ROTATIONAL SPEED = 8 000E 03 RPM FREQUENCY = 1 0764E 02 HZ					
BEARING TYPE					
NO. STN RADIAL ANGULAR					
1	2	6 6956E 05 9 2412E 02 4 5395E 05 2 2607E 02 3 0312E 04 2 2607E 02 1.7531E 05 1 5177E 02	16.0	Freq. Point No. 7 of 9	
2	29	8 9992E 05 1 1572E 03 5 6968E 05 2 7264E 02 4.9946E 04 2.7264E 02 2 1097E 05 1 7124E 02			
EXCITATION DATA					
*** TYPE ***		**** VERTICAL ****		**** HORIZONTAL ****	
NO STN FORCE MOMENT		IN-PHASE LAG		IN-PHASE LAG	
1	2	0 0000E-01 0 0000E-01 0 0000E-01 0 0000E-01		0 0000E-01	
2	11	0 0000E-01 0 0000E-01 0 0000E-01 0 0000E-01		0 0000E-01	
3	18	0 0000E-01 0 0000E-01 0 0000E-01 0 0000E-01		0 0000E-01	
4	29	1 0000E 00 0 0000E-01 0 0000E-01 0 0000E-01		0 0000E-01	
RESPONSE ORBIT					
ROTATIONAL SPEED = 8 000E 03 RPM FREQUENCY = 1 0764E 02 HZ				19.1	
NO STN LOCATION DISPL SLOPE		** PRINCIPAL RADII **		** INCLINATION **	
1 2 3 1496		MAJOR MINOR		REFERENCE	
2 11 13 5395		1 2915E-06-7 4782E-07 -1 6863E 01-S 077E 01		2 5661E-01	
3 18 21 5673		1 1586E-06-6 1553E-07 4 6899E 01-1 0483E 02		7 0609E-01	
4 29 37 8547		9 8842E-07-1 9568E-08 3 5405E 01-1 4405E 02		9 6117E-01	
		2 0700E-06-1 4802E-06 -2 7358E 01 1 2248E 02		1 6614E-01	

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TABLE 18 (CONT.)

LEVEL 2 BEARING DATA												Item Number	Remarks
ROTATIONAL SPEED = 8 0000E 03 RPM FREQUENCY = 1 1034E 02 HZ													
BEARING		TYPE	XX	YY	XY	YX	YY	YY	YY	YY	YY	16.0	Freq. Point No. 8 of 9
NO. STN		RADIAL ANGULAR											
1	2	*	6 695E 05	9 2412E 02	4 5395E 05	2 2607E 02	3 0312E 04	2 2607E 02	1 7531E 05	1 5177E 02			
2	29	*	8 993E 05	1 1572E 03	5 0968E 05	2 7264E 02	4 9946E 04	2 7264E 02	2 1097E 05	1 7124E 02			
EXCITATION DATA												19.1	
ROTATIONAL SPEED = 8 0000E 03 RPM FREQUENCY = 1 1034E 02 HZ													
NO. STN		LOCATION	DISPL	SLOPE	PRINCIPAL RADII	MINOR	INCLINATION	PHASE	ELLIPTICITY				
1	2	3.1486	*		1.1854E-06	-6 8638E-07	-1 9650E 01	-3 9871E 01	2 6659E-01				
2	11	13.5395	*		9.1316E-07	-5 5726E-07	5 2537E 01	-9 0971E 01	2 4203E-01				
3	18	21.5673	*		7 6545E-07	-3 4113E-08	3 2330E 01	-1 4626E 02	9 1467E-01				
4	29	37.8547	*		1 9784E-06	-1 4219E-06	-3 3774E 01	1 3053E 02	1 6367E-01				

TABLE 18 (CONT.)

LEVEL 2 BEARING DATA										FREQUENCY = 1 1310E 02 HZ										Item Number										Remarks																			
ROTATIONAL SPEED = 8 0000E 03 RPM																																																	
BEARING *** TYPE ***										***** XX *****										***** XY *****										***** YX *****										***** YY *****									
NO. STN										K										K										K										K									
1 2 *										6 6956E 05 9 2412E 02 4 5305E 05 2 2607E 02 3 0312E 04 2 2607E 02 1 7531E 05 1 5177E 02																																							
2 29 *										8 9933E 05 1 1572E 03 5 6968E 05 2 7264E 02 4 9946E 04 2 7264E 02 2 1097E 05 1 7125E 02																																							

TABLE 18 (CONT.)

										Item Number		Remarks	
										21.2		Mode No. 1	

TABLE 18 (CONT.)

Item Number									Remarks
I	FREQ	DAMP	MODAL MASS	DAMP RATIO	F-CHANGE	C-CHANGE	RESIDUE	D CHECK	
1	1 027D 02	4 001D 00	1 500D-01	1 299D-01	3 930D-04	-4 559D-06	1 285D-04	-2 286D-01	Mode No. 2
2	1 027D 02	4 001D 00	1 498D-01	1 301D-01	1 494D-05	-6 913D-07	2 014D-07	-2 287D-01	

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TABLE 18 (CONT.)

Mode No. 2 of 2 in Freq. Group No. 1												21.3
ROTATIONAL SPEED = 8.000E 03 RPM FREQUENCY = 1.0266E 02 HZ CRIT DAMP RATIO = 1.3008E-01 PRECISION INDEX = -2.2869E-01 NATURAL MODE SHAPE												
** PRINCIPAL RADII ** INCLINATION PHASE												
MAJOR MINOR (DEG) REFERENCE ELLIPTICITY												
NO	STM	LOCATION	DISPL	SLOPE								
1	2	3.1496	*	*	2.4206E-01	-1.1432E-01	4.5042E 01	5.1253E 01	3.5845E-01			
2	11	13.5395	*	*	1.4276E 00	-2.4464E-01	1.5216E 01	1.3154E 01	7.0741E-01			
3	18	21.5673	*	*	1.7127E 00	-2.8725E-01	1.3353E 01	1.1073E 01	7.1275E-01			
4	29	37.8547	*	*	1.3626E-01	9.1211E-03	3.5805E 01	3.4396E 01	8.7452E-01			
RESONANT RESPONSE												
EXCITATION DATA												
**** TYPE ****												
NO STM FORCE MOMENT												
**** VERTICAL ****												
IN-PHASE LAG IN-PHASE LAG												
NO	STM	LOCATION		DISPL		SLOPE						
1	2	*		*								
2	11	*		*								
3	18	*		*								
4	29	*		*								
**** HORIZONTAL ****												
IN-PHASE LAG IN-PHASE LAG												
NO	STM	LOCATION		DISPL		SLOPE						
1	2	*		*								
2	11	*		*								
3	18	*		*								
4	29	*		*								
RESPONSE ORBIT												
** PRINCIPAL RADII ** INCLINATION PHASE												
MAJOR MINOR (DEG) REFERENCE ELLIPTICITY												
NO	STM	LOCATION		DISPL		SLOPE						
1	2	3.1496		*		*		2.1417E-06 5.3578E-07 -4.8344E 01 1.1967E 02 5.9279E-01				
2	11	13.5395		*		*		2.9368E-06-5.2480E-08 -1.5849E 01 1.6459E 02 9.6489E-01				
3	18	21.5673		*		*		2.7486E-06 1.2159E-07 1.5922E 00-1.7894E 02 9.1527E-01				
4	29	37.8547		*		*		3.3333E-06 5.0853E-07 -5.1830E 01-6.8985E 01 7.3527E-01				

Response orbits at frequencies which span each frequency range are listed in order. The input set-up required the response to be calculated at damped natural frequencies and allowed up to two damped natural modes to be found in each frequency range. The record of iteration progression in the process of finding the damped natural mode is to be printed out and starting values for the iterative processes are furnished according to the results of stability analysis, which will be discussed in the next section.

For the first frequency range, the iteration record shows convergence to be reached in two cycles for the first mode. The rapid convergence is expected because the starting values are actually the converged solution obtained from the stability analysis. Improvement achieved by iteration steps is beyond the resolution of the output format. There is no other mode expected in this frequency range, therefore, the same starting values are used for finding the "non-existing" second mode. The iteration record shows 20 cycles without achieving convergence. Additional discussions on the iteration record will be found in Section 3.4.5. The damped natural frequency of 68.11 Hz is seen to be quite close to the undamped approximation of 68.62 Hz. The critical damping ratio of 0.030 suggests a rather modest stability margin. Amplitude distribution of the major radii is not too different from the amplitude distribution of the undamped, isotropic mode shape. All orbit parameters are fairly uniform. The minor radius is less than (1/5) of the major radius at all stations, indicating substantial anisotropy of the system. Since the minor radii are all positive, the orbits are co-rotational. Response amplitude at station 18, where the unit excitation is located, shows a major radius of 3.34×10^{-4} in. This is over 30 times larger than that calculated at 68.05 Hz, which is the closest assigned frequency. Clearly, if the system is not highly damped, it is important that response be calculated precisely at the natural frequency.

In the second frequency range, convergence is similarly rapid for both modes. The natural mode shapes have very similar distributions of major radii. The minor radii of the mode at 102.66 Hz are algebraically smaller than those of the mode at 97.57 Hz at all stations, however the differences are very small. There are no clear-cut shape features to distinguish those two modes. The values of the critical damping ratio are quite different. The mode at 97.57 Hz is not well damped, critical damping ratio = 0.032, and the resonant response to the "misplaced" excitation is more or less similar to the natural mode shape and the amplitudes at all stations are significantly higher than those at the nearest assigned frequency of 97.51 Hz. The mode at 102.66 Hz is fairly well damped. The resonant response to the "misplaced" excitation no longer resembles the natural mode shape, and peaks only moderately above the response at the nearest assigned frequency of 102.45 Hz.

3.4.5 Stability Analysis (IRUN = 5)

From the second run of asynchronous resonance analysis, estimates can be made on the approximate frequencies of the damped natural modes. In fact, one might as well use the same speed-frequency combinations of the asynchronous resonance analysis. Pre-stored intermediate data can be accessed in lieu of repeating Level I calculations. One mode is expected in the first frequency range, while two modes are expected in the second frequency range. Thus, the single input set-up, which covers both frequency ranges, specifies two modes to be sought in each frequency range. The second frequency range is somewhat wider than if only one mode is to be sought (see Section 2.2), nine frequency points are used to divide up this range, two more points than the number used for the first frequency range to ensure computation accuracy.

Since there is as yet no clue on the approximate value of damping associated with various modes, a first trial was run allowing the program to use its internal logic to initiate the iteration process. The output of this run is given as Table 19.

TABLE 19
COMPUTER OUTPUT OF STABILITY ANALYSIS
FIRST TRIAL WITH INTERNAL STARTING LOGIC

(From Input Data of Table 10)

8 Sheets

*****CALCULATION SUMMARY*****	Item Number	Group
TEST IRUN=3,4,5 LUND ROTOR ASYNCHRONOUS BENDING ANALYSIS	14.3	Freq. Group No. 1
WHIRL STABILITY ANALYSIS		
BENDING EXCITATION STATIONS 2 11 18 29		

TABLE 19 (CONT.)

Item Number										Remarks	
I	FREQ	DAMP	MODAL MASS	DAMP RATIO	F-CHANGE	C-CHANGE	RESIDUE	6	CHECK	21.2	Mode No. 1
1	6 805D 01	0 000D-01	3 627D-01	0 000D-01	2 484D-01	1 246D 00	2 754D 04	1	724D-01		
2	6 830D 01	1 246D 00	3 172D-01	2 876D-02	-1 892D-01	1 182D-01	3 558D 02	-1	509D-02		
3	6 811D 01	1 364D 00	3 328D-01	2 876D-02	7 413D-03	-7 284D-03	1 132D 00	-1	509D-02		
4	6 811D 01	1 357D 00	3 322D-01	2 999D-02	6 991D-06	-1 799D-05	4 941D-06	-3	672D-02		

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TABLE 19 (CONT.)

Item Number										Remarks
I	FREQ	DAMP	MODAL MASS	DAMP RATIO	F-CHANGE	C-CHANGE	RESIDUE	D	CHECK	21.2 Mode No. 2
1	6.585D	01	0.000D-01	-4.360D-02	0.000D-01	-2.936D-03	-9.775D-01	4.937D-08	0.000D-01	
LOWER-BOUND RESET										
2	6.300D	01	-9.288D-01	-1.414D-02	5.211D-01	-4.447D-03	-1.572D-02	1.185D-09	2.440D-00	
3	6.805D	01	-2.501D-00	-2.584D-01	7.110D-02	-7.366D-01	7.336D-06	2.313D-08	-1.490D-00	
4	6.731D	01	4.836D-00	-2.664D-02	-1.348D-00	4.698D-00	1.642D-01	4.408D-07	1.808D-00	
5	7.201D	01	5.000D-00	-2.866D-02	-1.212D-00	4.933D-00	3.406D-02	4.792D-06	1.241D-00	
UPPER-BOUND RESET										
6	7.350D	01	5.010D-00	-5.086D-02	-6.702D-01	4.115D-00	6.766D-03	2.479D-06	9.101D-01	
7	6.805D	01	5.017D-00	-2.557D-02	-1.442D-00	4.832D-00	1.434D-01	3.056D-07	1.739D-00	
8	7.288D	01	5.160D-00	-3.465D-02	-1.442D-00	4.604D-00	1.415D-02	3.325D-06	1.739D-00	
UPPER-BOUND RESET										
9	7.350D	01	5.162D-00	-4.593D-02	-7.645D-01	4.101D-00	1.035D-02	2.491D-06	9.545D-01	
10	6.805D	01	5.172D-00	-2.759D-02	-1.378D-00	4.705D-00	1.297D-01	3.134D-07	1.647D-00	
11	7.275D	01	5.302D-00	-3.188D-02	-1.378D-00	4.654D-00	1.716D-02	3.544D-06	1.647D-00	
UPPER-BOUND RESET										
12	7.350D	01	5.305D-00	4.239D-02	-8.513D-01	4.086D-00	1.462D-02	2.505D-06	9.943D-01	
ITERATION OSCILLATES AFTER 12 TRIALS FOR ROOT# 2										

TABLE 19 (CONT.)

Item Number										Remarks	
ROTATIONAL SPEED = 8 000E 03 RPM FREQUENCY = 6 8114E 01 HZ CRIT DAMP RATIO = 2 9986E-02 PRECISION INDEX = -3 6721E-02 NATURAL MODE SHAPE										21.3	
** PRINCIPAL RADII ** INCLINATION PHASE MAJOR MINOR (DEG) REFERENCE ELLIPTICITY										Freq. Group No. 1	
NO	STN	LOCATION	DISPL	SLOPE							
1	2	3 1496	*		1 0790E 00	2 1341E-01	-5 5313E 01-4	1353E 01	6 6976E-01		
2	11	13 5395	*		1 6280E 00	2 8776E-01	-5 4080E 01-4	1643E 01	6 9959E-01		
3	18	21 5673	*		1 7083E 00	2 9165E-01	-5 3956E 01-4	0753E 01	7 0835E-01		
4	29	37 8547	*		8 6442E-01	1 5431E-01	-5 7041E 01-4	4088E 01	6 9706E-01		

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TABLE 19 (CONT.)

Item Number	Remarks
*****CALCULATION SUMMARY***** TEST IRUN=3,4,5 LUND ROTOR ASYNCHRONOUS BENDING ANALYSIS WHIRL STABILITY ANALYSIS BENDING EXCITATION STATIONS 2 11 18 29	14.0 Frequency Group No. 2

TABLE 19 (CONT.)

I	FREQ	DAMP	MODAL MASS	DAMP RATIO	F-CORRECTION	C-CORRECTION	RESIDUE	D CHECK	Item Number	Remarks
1	1 0240 02	0 0000-01	2 5070-01	0 0000-01	-4 2030-02	4 1830-01	1 5800-01	3 8060-01	21.2	Mode No. 1
2	9 8250 01	4 1560 00	3 2770-01	6 4530-02	-4 0840-01	-2 4020-00	6 7570-02	-2 2800-01		
3	9 7840 01	1 7540 00	3 5790-01	2 5050-02	-2 4110-01	5 0350-01	7 3730-03	7 2160-02		
4	9 7600 01	2 2630 00	3 5940-01	2 5050-02	-2 4140-02	6 5310-03	1 1230-05	7 2160-02		
5	9 7570 01	2 2560 00	3 6020-01	3 2130-02	1 4000-02	1 4720-05	2 3890-10	2 5435-02		
6	9 7570 01	2 2560 00	3 6020-01	3 2100-02	2 4730-03	-2 5720-10	9 9250-20	2 5430-02		

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TABLE 19 (CONT.)

I	FREQ	DAMP	MODAL MASS	C-RATIO	F-CHANGE	Q-CHANGE	PERIOD	CHECK		Item Number	Remarks
								Q	PERIOD		
1	1 0240 02	0 0000-01	2 1550-03	0 0090-01	2 3200 01	2 0620-01	6 1500 01	-1	1590 00		
UPPER-BOUND RESET											
2	1 1310 02	9 4630-02	5 3770-03	7 7850-02	3 5110 00	1 0750-01	1 3980 01	-2	3630-01		
3	1 0240 02	2 0220-01	2 1360-03	7 7850-02	2 2750 01	1 0180-01	5 9420 01	-2	3630-01		
UPPER-BOUND RESET											
4	1 1310 02	2 8230-01	5 3600-03	7 7850-02	3 4710 00	1 1210-01	1 3430 01	-2	3630-01		
5	1 0240 02	3 9630-01	2 2510-03	8 6570-01	1 1820 01	1 5710-01	5 7630 01	-1	3670 00	21.2	Mode No. 2
UPPER-BOUND RESET											
6	1 1310 02	4 7530-01	5 3460-03	8 6970-01	2 3430 00	1 0860-01	1 3010 01	-1	3670 00		
7	1 0240 02	5 8430-01	2 3520-03	1 2130 00	1 9730 01	1 3290-01	5 6100 01	-1	4240 00		
UPPER-BOUND RESET											
8	1 1310 02	6 5540-01	5 3330-03	5 4340-01	2 2430 00	1 0910-01	1 4590 01	-4	7030-01		
ITERATION OSCILLATES AFTER 8 TRIALS FOR ROOT# 2											

TABLE 10 (CONT.)

ROTATIONAL SPEED = 8 000E-03 RPM FREQUENCY = 3 757E-01 Hz CRIT DAMP RATIO = 2 209E-02 PRECISION INDEX = 2 528E-02 NATURAL MODE SHAPE					Item Number	Remarks	
NO	SIN	LOCATION	DISPL	SLOPE	21.3	Mode No. 1	
1	2	3.183	*	*			
2	11	13.153	*	*			
3	13	21.824	*	*			
4	20	21.824	*	*			
** PRINCIPAL MODES							ELLIPTICITY
MAJOR							MINOR
1 0.00000000							1 0.00000000
2 0.00000000							2 0.00000000
3 0.00000000							3 0.00000000
4 0.00000000							4 0.00000000
5 0.00000000							5 0.00000000
6 0.00000000							6 0.00000000
7 0.00000000							7 0.00000000
8 0.00000000							8 0.00000000
9 0.00000000							9 0.00000000
10 0.00000000							10 0.00000000
11 0.00000000							11 0.00000000
12 0.00000000							12 0.00000000
13 0.00000000							13 0.00000000
14 0.00000000							14 0.00000000
15 0.00000000							15 0.00000000
16 0.00000000							16 0.00000000
17 0.00000000							17 0.00000000
18 0.00000000							18 0.00000000
19 0.00000000							19 0.00000000
20 0.00000000							20 0.00000000
21 0.00000000							21 0.00000000
22 0.00000000							22 0.00000000
23 0.00000000							23 0.00000000
24 0.00000000							24 0.00000000
25 0.00000000							25 0.00000000
26 0.00000000							26 0.00000000
27 0.00000000							27 0.00000000
28 0.00000000							28 0.00000000
29 0.00000000							29 0.00000000
30 0.00000000							30 0.00000000
31 0.00000000							31 0.00000000
32 0.00000000							32 0.00000000
33 0.00000000							33 0.00000000
34 0.00000000							34 0.00000000
35 0.00000000							35 0.00000000
36 0.00000000							36 0.00000000
37 0.00000000							37 0.00000000
38 0.00000000							38 0.00000000
39 0.00000000							39 0.00000000
40 0.00000000							40 0.00000000
41 0.00000000							41 0.00000000
42 0.00000000							42 0.00000000
43 0.00000000							43 0.00000000
44 0.00000000							44 0.00000000
45 0.00000000							45 0.00000000
46 0.00000000							46 0.00000000
47 0.00000000							47 0.00000000
48 0.00000000							48 0.00000000
49 0.00000000							49 0.00000000
50 0.00000000							50 0.00000000
51 0.00000000							51 0.00000000
52 0.00000000							52 0.00000000
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54 0.00000000							54 0.00000000
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56 0.00000000							56 0.00000000
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60 0.00000000							60 0.00000000
61 0.00000000							61 0.00000000
62 0.00000000							62 0.00000000
63 0.00000000							63 0.00000000
64 0.00000000							64 0.00000000
65 0.00000000							65 0.00000000
66 0.00000000							66 0.00000000
67 0.00000000							67 0.00000000
68 0.00000000							68 0.00000000
69 0.00000000							69 0.00000000
70 0.00000000							70 0.00000000
71 0.00000000							71 0.00000000
72 0.00000000							72 0.00000000
73 0.00000000							73 0.00000000
74 0.00000000							74 0.00000000
75 0.00000000							75 0.00000000
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77 0.00000000							77 0.00000000
78 0.00000000							78 0.00000000
79 0.00000000							79 0.00000000
80 0.00000000							80 0.00000000
81 0.00000000							81 0.00000000
82 0.00000000							82 0.00000000
83 0.00000000							83 0.00000000
84 0.00000000							84 0.00000000
85 0.00000000							85 0.00000000
86 0.00000000							86 0.00000000
87 0.00000000							87 0.00000000
88 0.00000000							88 0.00000000
89 0.00000000							89 0.00000000
90 0.00000000							90 0.00000000
91 0.00000000							91 0.00000000
92 0.00000000							92 0.00000000
93 0.00000000							93 0.00000000
94 0.00000000							94 0.00000000
95 0.00000000							95 0.00000000
96 0.00000000							96 0.00000000
97 0.00000000							97 0.00000000
98 0.00000000							98 0.00000000
99 0.00000000							99 0.00000000
100 0.00000000							100 0.00000000

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In the frequency range, convergence of iteration for the first mode was reached after four cycles. There being no second mode, the search effort resulted in repeated attempts to exceed the upper bound of the frequency range. The residue shows no definite trend of reducing. The modal mass consistently shows an anomalous negative value. The natural frequency and the critical damping ratio are exactly equal to those given in Table 18 as far as the available digits reveal. The mode shape parameters are slightly different owing to a somewhat larger residue at the last cycle of iteration. In the second frequency range, convergence of iteration for the first mode was reached after six cycles, with an extremely small residue at the end. Search for the second mode, however, did not succeed. The iteration process developed an oscillating pattern. A closer look revealed that after each oscillating cycle, the residue does reduce monotonically. Therefore, the attempt to find the second mode in this frequency range was continued afterwards. Modal parameters of the first mode at 97.57 Hz are identical to those given in Table 18.

A second trial was made using converged solutions of the first modes in each frequency range as the respective starting values. For the second set of starting values, the first set was repeated in the first frequency range since another mode is really not expected. The designated values for continuation as shown by the previous iteration record was used as the second set in the second frequency range. The second trial still failed to establish the second mode in the second frequency range. Previously noted trend of a monotonically reducing residue persisted at a moderate pace. Therefore, a third trial was made with the starting damping value "accelerated" beyond the trend indicated by the iteration record of the second trial. This time convergence was reached in four cycles. Iteration records pertaining to the second mode in the second frequency range are shown in Table 20.

TABLE 20

COMPUTER OUTPUT FOR STABILITY ANALYSIS
 ITERATION RECORDS OF SECOND AND THIRD TRIALS WITH USER FURNISHED STARTING VALUES
 (From Input Data of Tables 11 and 12)

11 Sheets

*****CALCULATION SUMMARY*****		Item Number	Remarks
TEST IRUN=3,4, LUND ROTOR ASYNCHRONOUS BENDING ANALYSIS		14.0	Freq. Group No. 2, 2nd Trial
WHIRL STABILITY ANALYSIS			
BENDING EXCITATION STATIONS 2 11 18 29			

TABLE 23 (CONT.)

I	FREQ	DAMP	MODAL MASS	DAMP RATIO	F-CHANGE	C-CHANGE	RESIDUE	Item Number		Remarks
1	6.8110	01	1.3370 00	3.3230-01	2.9980-02	4.0750-04	2.6310-04	1.9130-03	-3	D CHECK
2	6.8110	01	1.3370 00	3.3220-01	2.9990-02	4.4860-08	3.2350-08	2.5960-11	-3	6670-02
										6720-02
								21.2		Mode No. 1, 2nd Trial

TABLE 20 (CONT.)

I	FREQ	DAMP	MODAL MASS	DAMP RATIO	F-CHANGE	C-CHANGE	RESIDUE	D CHECK	Item Number	Remarks
1	6.8110 01	1.3570 00	2.5620-02	3.8880-01	1.7690-02	5.2760-04	1.8330 03	-4.3800-01		
2	6.8130 01	1.3570 00	2.5690-02	3.8770-01	3.0500-04	4.6120-04	4.7880 02	-4.2670-01		
3	6.8130 01	1.3580 00	2.5690-02	3.8790-01	2.9770-04	4.0860-04	3.7680 02	-4.2710-01		
4	6.8130 01	1.3580 00	2.5680-02	3.8790-01	-2.6390-04	3.6190-04	2.9550 02	-4.2710-01		
5	6.8130 01	1.3590 00	2.5680-02	3.8830-01	-2.3390-04	3.2050-04	2.3180 02	-4.2790-01		
6	6.8130 01	1.3590 00	2.5670-02	3.8850-01	-2.0720-04	2.8390-04	1.8180 02	-4.2820-01		
7	6.8130 01	1.3590 00	2.5670-02	3.8860-01	-1.8360-04	2.5150-04	1.4260 02	-4.2850-01		
8	6.8130 01	1.3600 00	2.5670-02	3.8870-01	-1.6270-04	2.2270-04	1.1180 02	-4.2870-01		
9	6.8130 01	1.3600 00	2.5660-02	3.8890-01	-1.4410-04	1.9730-04	8.7730 01	-4.2890-01		
10	6.8130 01	1.3600 00	2.5660-02	3.8900-01	-1.2770-04	1.7470-04	6.9810 01	-4.2910-01	21.2	Mode No. 2, 2nd Trial
11	6.8130 01	1.3600 00	2.5660-02	3.8900-01	-1.1310 4	1.5480-04	5.3970 01	-4.2930-01		
12	6.8130 01	1.3600 00	2.5660-02	3.8910-01	-1.0020-04	1.3710-04	4.2330 01	-4.2940-01		
13	6.8130 01	1.3600 00	2.5650-02	3.8910-01	-8.8790-05	1.2140-04	3.3210 01	-4.2940-01		
14	6.8130 01	1.3610 00	2.5650-02	3.8920-01	-7.8650-05	1.0750-04	2.6550 01	-4.2970-01		
15	6.8130 01	1.3610 00	2.5650-02	3.8920-01	-6.9670-05	9.5240-05	2.0430 01	-4.2970-01		
16	6.8130 01	1.3610 00	2.5650-02	3.8930-01	-6.1720-05	8.4350-05	1.6020 01	-4.2990-01		
17	6.8130 01	1.3610 00	2.5650-02	3.8940-01	-5.4670-05	7.4710-05	1.2570 01	-4.3000-01		
18	6.8130 01	1.3610 00	2.5650-02	3.8940-01	-4.8420-05	6.6170-05	9.8590 00	-4.3010-01		
19	6.8130 01	1.3610 00	2.5650-02	3.8950-01	-4.2890-05	5.8600-05	7.7340 00	-4.3010-01		
20	6.8130 01	1.3610 00	2.5650-02	3.8950-01	-3.7990-05	5.1900-05	6.0660 00	-4.3020-01		

AFTER 20 ITERATIONS, NO EIGENVALUE IS FOUND.

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TABLE 20 (CONT.)

ROTATIONAL SPEED = 8.0000E 03 RPM FREQUENCY = 6.8114E 01 HZ CRIT DAMP RATIO = 2.9986E-02 PRECISION INDEX = -3.6718E-02 NATURAL MODE SHAPE									
NO.	SIN	LOCATION	DISPL	SLOPE	** PRINCIPAL RADII		** INCLINATION		PHASE REFERENCE
					MAJOR	MINOR	(DEG)		
1	2	3.1496	*		1.1335E 00	2.0729E-01	-5.5521E 01	-4.1272E 01	ELLIPTICITY
2	11	13.5395	*		1.6911E 00	2.3654E-01	-5.6117E 01	-4.4358E 01	6.9089E-01
3	18	21.5673	*		1.7703E 00	2.2968E-01	-5.6353E 01	-4.5323E 01	7.5458E-01
4	29	37.8547	*		9.0723E-01	1.5079E-01	-5.7265E 01	-4.4330E 01	7.7032E-01
									7.1496E-01
									21.3
									Mode No. 1, 2nd Trial

TABLE 20 (CONT.)

Item Number		Remarks
*****CALCULATION SUMMARY*****		
TEST IRUM-3,4,5 LUND ROTOR ASYNCHRONOUS BENDING ANALYSIS		
WHIRL STABILITY ANALYSIS		
BENDING EXCITATION STATIONS		
2	11 18 29	
14.0		Freq. Group No. 2, 2nd Trial

TABLE 20 (CONT.)

I	FREQ	DAMP	MODAL MASS	DAMP RATIO	F-CHANGE	C-CHANGE	RESIDUE	D CHECK	Item Number	Remarks
1	9.7370	01	2.2560	00	3.6020-01	3.2090-02	-3.7510-04	2.3800-04	3.2740-09	2.5430-02
2	9.7370	01	2.2560	00	3.6020-01	3.2100-02	3.3880-09	-1.8780-08	9.6270-18	2.5430-02
									21.2	Mode No. 1, 2nd Trial

TABLE 20 (CONT.)

I	FREQ	DAMP	MODAL MASS	DAMP RATIO	F-CHANGE	C-CHANGE	RESIDUE	D CHECK	Item Number	Remarks
1	1.024D 02	7.646D-01	2.446D-03	3.895D-01	1 879D 01	1.108D-01	5 516D 01	-4 302D-01		
UPPER-BOUND RESET										
2	1.131D 02	8.277D-01	5.321D-03	3.895D-01	8.189D 00	1.099D-01	1.217D 01	-4 302D-01		
3	1.024D 02	9.376D-01	2.675D-03	1.711D 00	1 699D 01	8 918D-02	5 374D 01	-1.443D 00		
UPPER-BOUND RESET										
4	1.131D 02	9.935D-01	5.311D-03	8 269D-01	8.109D 00	1.106D-01	1.178D 01	-6.140D-01		
5	1.024D 02	1.104D 00	2.905D-03	1.855D 00	1.546D 01	7.065D-02	5.286D 01	-1.413D 00	21.2	Mode No. 2, 2nd Trial
UPPER-BOUND RESET										
6	1.131D 02	1.153D 00	5.303D-03	1.855D 00	8 029D 00	1.113D-01	1.142D 01	-1 413D 00		
7	1.024D 02	1.264D 00	3.185D-03	1.855D 00	1.397D 01	5.475D-02	5 216D 01	-1.413D 00		
UPPER-BOUND RESET										
8	1.131D 02	1.306D 00	5.295D-03	1.090D 00	7.949D 00	1.120D-01	1.108D 01	-7.481D-01		
ITERATION OSCILLATES AFTER 8 TRIALS FOR ROOT# 2										

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TABLE 20 (CONT.)

ROTATIONAL SPEED = 8.0000E 03 RPM FREQUENCY = 9.7573E 01 HZ CRIT DAMP RATIO = 3.2096E-02 PRECISION INDEX = 2.5428E-02 NATURAL MODE SHAPE										Item Number	Remarks
NO.	STN	LOCATION	DISPL	SLOPE	** PRINCIPAL RADII		** INCLINATION	PHASE	ELLIPTICITY		
					MAJOR	MINOR	(DEG)	REFERENCE			
1	2	3.1496	*		3.0138E-01	4.9344E-02	4.7018E 01	4.3296E 01	7.1861E-01	21.3	Mode No. 1, 2nd Trial
2	11	13.5395	*		1.5780E 00	-6.1414E-02	1.4480E 01	1.4009E 01	9.2508E-01		
2	18	21.5673	*		1.8817E 00	-1.1828E-01	1.3263E 01	1.2414E 01	8.8172E-01		
4	29	37.8547	*		1.8765E-01	8.5406E-02	5.7390E 01	4.2713E 01	3.7444E-01		

TABLE 20 (CONT.)

I	FREQ	DAMP	MODAL MASS	DAMP RATIO	F-CHANGE	C-CHANGE	RESTDUE	D CHECK	Item Number		Remarks
1	9.7570	01	2.2560	00	3.6020-01	3.2090-02	-3 7510-04	2 3800-04	3 2740-09	2.5450-02	Mode No. 1, Freq. Group No. 2, 3rd Trial
2	9.7570	01	2.2560	00	3.6020-01	3.2100-02	3 5880-09	-1 8780-08	9 6270-18	2.5430-02	

TABLE 20 (CONT.)

I	FREQ	DAMP	MODAL MASS	DAMP RATIO	F-CHANGE	C-CHANGE	RESIDUE	D CHECK	Item Number	Remarks
1	1.0240 02	4.0000 00	3.4280-01	5.6980-02	2 2370-01	1 7240-03	8 0790 01	-1 9800-01	21.2	Mode No. 2, Freq. Group No. 2, 3rd Trial
2	1.0260 02	4.0020 00	1.6600-01	1.1750-01	3 5040-02	-2 2490-04	1 1340 00	-2 2060-01		
3	1.0270 02	4.0010 00	1.5050-01	1.2950-01	1 7140-03	-2 0350-05	2 4560-03	-2 2820-01		
4	1.0270 02	4.0010 00	1.4980-01	1.3010-01	6 8450-05	-3 0520-06	4 2080-06	-2 2870-01		

TABLE 20 (CONT.)

Item Number				Remarks			
21.3				Mode No. 1, Freq. Group No. 2, 3rd Trial			
ROTATIONAL SPEED = 8.000E 03 RPM FREQUENCY = 9.7573E 01 HZ CRIT DAMP RATIO = 3.2096E-02 PRECISION INDEX = 2.5428E-02 NATURAL MODE SHAPE							
NO.	STN	LOCATION	DISPL SLOPE	** PRINCIPAL RADII ** MAJOR MINOR	** INCLINATION (DEG)	PHASE REFERENCE	ELLIPTICITY
1	2	3.1496	*	3.0138E-01 4.9344E-02	4.7018E 01 4.3296E 01		7.1861E-01
2	11	13.5395	*	1.5780E 00-6.1414E-02	1.4480E 01 1.4009E 01		9.2508E-01
3	18	21.5673	*	1.8817E 00-1.1828E-01	1.3263E 01 1.2414E 01		8.8172E-01
4	29	37.8547	*	1.8765E-01 8.5406E-02	5.7390E 01 4.2713E 01		3.7444E-01
ROTATIONAL SPEED = 8.000E 03 RPM FREQUENCY = 1.0266E 02 HZ CRIT DAMP RATIO = 1.3010E-01 PRECISION INDEX = -2.2868E-01 NATURAL MODE SHAPE						Mode No. 2, Freq. Group No. 2, 3rd Trial	
NO.	STN	LOCATION	DISPL SLOPE	** PRINCIPAL RADII ** MAJOR MINOR	** INCLINATION (DEG)	PHASE REFERENCE	ELLIPTICITY
1	2	3.1496	*	2.4206E-01-1.1432E-01	4.5042E 01 5.1253E 01		3.5845E-01
2	11	13.5395	*	1.4276E 00-2.4464E-01	1.5216E 01 1.3154E 01		7.0742E-01
3	18	21.5673	*	1.7127E 00-2.8725E-01	1.3353E 01 1.1073E 01		7.1275E-01
4	29	37.8547	*	1.3626E-01 9.1212E-03	3.5803E 01 3.4396E 01		8.7452E-01

SECTION IV

THEORETICAL OVERVIEW

Rotordynamic analysis, in the manner treated here, deals with a linear system. As such, much of the analytical methods which were developed for linear control systems would be applicable. One can indeed go quite far to enumerate analogous concepts between the fields of rotordynamics and linear controls. It is quite appropriate to regard a rotor system as a multi-terminal "black box." Much of the mathematical operations involved in rotordynamic analysis concerns the "transfer functions" of the "black box." The practical aspects of rotor engineering, however, require an understanding of the restrictions of the simplifying assumptions which underlie the method of analysis and an understanding of the general characteristics of rotor systems which may take on special significance as dictated by particular design features and operating environments. To address these issues, the subject matter has to be identified as a high speed rotor system, not merely a linear black box. The present section will examine the "anatomy" of rotordynamic analysis. While the accompanying software specifically utilizes the "frequency-response" approach as a starting point, the physical ideas to be discussed here are less restrictive. Details of mathematical derivations are contained in Sections V and VI. Immediate attention here is directed toward basic concepts.

4.1 Idealized Rotor Structure

While the historical evolution of rotordynamic studies began by emulating the analysis of beam-like structures, the contemporary point of view recognizes two important distinctive features in the dynamic features of a high speed rotor; they are

- o gyroscopic inertia, and
- o support compliance

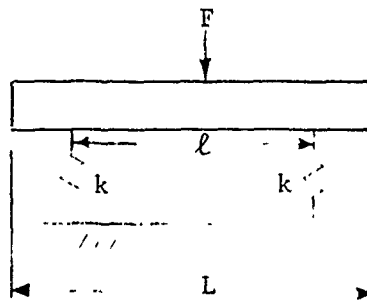
4.1.1 Gyroscopic Effect

In normal operations of a rotor, even during startup and shutdown transients, the rotational speed can be treated as a constant for

lateral motions of the rotor. Since functional requirements of the machinery generally include a well defined rotational axis relative to its platform, any inclination-deflection of the shaft-axis is presumably small. Furthermore, in comparison with the rotational speed, the angular rate of any platform motion is probably quite small. Under these circumstances, Euler's Law for angular motions can be reduced to a cross-axis coupling of the gyroscopic inertia. A thorough derivation of this idea is presented in Appendix A. The consequence of cross-axis gyroscopic coupling is two fold. First of all, lateral motions of the rotor generally would not be planar -- the shaft center motion would typically describe an elliptic orbit. In fact, if rotational symmetry prevails in the rotor system, the orbit would be circular. Secondly, each free vibration mode of the equivalent non-rotating shaft is split into two modes which are distinguishable not only in the natural frequency, but also in the sense of rotation of the whirl motion (relative to the shaft rotation).

4.1.2 Rotor Flexibility

Rotor flexibility is increasingly of importance as mechanical equipment keeps up its pace with technological sophistication. The word "flexibility", however, is a relative quantity in the context of rotordynamic phenomena. Since the main external constraints on the rotor axis are the bearing supports, bearing compliance is in fact the natural reference for rotor flexibility. This idea can be illustrated by a simple example as depicted in the following sketch. Here, a concentrated load is applied to the midpoint of a uniform beam which is supported from the ground by two springs of equal stiffness.



The total deflection at the applied force is the sum of beam deflection $\frac{F\ell^3}{48EI}$ and spring deflection $\frac{F}{2k}$. The ratio of these two quantities, $\frac{k\ell^3}{24EI}$, can be regarded as the "static flexibility index."

It is noted that in such an example the overhung portions of the beam have no contribution to static "flexibility". Also, the applied force F is not an explicit parameter. However, it is evident that its location, as well as the span between the springs, defines the physical setup. In a realistic rotor, the rigidity parameter EI would have to represent an average, and the "static flexibility index" reflects the relative insensitivity of the influence of the bearing stiffness on the two lowest natural modes of the rotor. For higher natural modes, the ratio of the bearing span to the characteristic wave length of bending vibration may be considered to be the "dynamic flexibility index" $\ell\sqrt{\omega}/(EI/\rho A)^{1/4}$. This index represents the relative ineffectiveness of support bearings in controlling lateral vibrations of the rotor.

4.1.3 Modeling of Shafting Structure

Shafting can be structurally modeled as a succession of beam segments which are rigidly connected to each other.

Division of the rotor into interconnected segments is necessary to accommodate variations in shaft cross-sections and/or materials, the attachment of wheel-like appendages as rigid bodies, the presence of bearing constraints, and sources of dynamic excitation. A common first approximation is to assume the inter-segmental junction as a boundary across which deflection, slope, and twist are continuous, whereas jumps in various other physical quantities are allowed to take place as required. Theories of torsion and flexure for slender prismatic bars are commonly used to deal with the structural aspects of the shaft segments. In the original treatments of Holzer and Myklestad, lineal inertia effects are

assigned to the ends of the segment while the segment itself is regarded as a massless torsion or flexure spring. In so doing, each inter-segmental junction becomes automatically a triplet of degrees of freedom, one for torsion and one each for flexure in the two lateral planes. Since closed-form solutions of a uniform shaft with distributed inertia are available for both the torsion and the flexure problems, they can be incorporated into a rotor-dynamic analysis. The main advantage of the latter approach is to allow rotor modeling of slender shaft segments without subdividing. Otherwise, employing the lumped-parameter method in the manner of Holzer and Myklestad, it is necessary to subdivide slender segments such that the length of each subdivided segment is about equal to its diameter. The second order flexure theory, which includes the effects of rotary inertias and shear deformation can also be incorporated to improve accuracy of analysis for higher order flexure modes. In actual practice, however, uncertainties in the treatments of junctions and attached appendages probably would obscure the improvements gained through the use of second order flexure theory. Accuracy of the slender bar theory of flexure also becomes degraded when a rotor of rather stubby proportions is analyzed. In such a circumstance, the important rotor motions are probably rigid body-like; and the slender bar theory is amiss in neglecting the rotary inertias. Shear deformation may be of increased importance relative to flexure, but since the motion is predominantly due to bearing support compliance, it is not essential to refine the elastic aspect of the flexure theory. The software prepared here makes use of the distributed analyses of slender bars, while lumped correction is made for rotary inertias. Omission of possible contribution of shear deformation on high order flexure modes is recognized as an inherent shortcoming; this should appear mainly in some uncertainty in the estimated natural frequencies of the higher modes but should not contribute significantly to the estimated mode shapes.

4.1.4 Dynamic Degrees of Freedom

The rotor model described above allows estimates to be made on responses to excitations and the conditions of resonances. Each inter-segmental junction may be considered to be a location of potential excitation. For the present discussion simple harmonic temporal dependence is assumed for all excitations. An excitation may be any combination of torsion, lateral force, and lateral moment. Since the lateral force and the lateral moment may be in either of the two mutually perpendicular planes, there can be up to four independent degrees of freedom for flexure excitation. The torsional motion is basically uncoupled from the flexural motions in the sense that a torsional moment would not induce a flexural motion and a lateral force or moment would not result in a torsional twist. There may of course be simultaneous torsional and flexural excitations such as through a gear mesh. Flexural motions in the two lateral planes are coupled through gyroscopic inertia in the conventional Cartesian coordinate system. Prevailing symmetry, however, allows the flexural motion to be described in a pair of whirl components, which have opposite senses of rotation and are uncoupled from each other, provided the bearing support characteristics are isotropic.

4.1.5 Mobility and Stiffness Matrices

Corresponding to the excitation components of torsional moment, lateral force, and lateral moment, the response consists of displacement components of torsional twist, lateral deflection, and lateral slope at each junction. A complete description of the response of the system per unit of each excitation is given by the influence coefficients which form the mobility or response matrix. This matrix is the analog of a transfer function of a control system. The inverse of the mobility matrix is the impedance or stiffness matrix. For a given shafting model, these matrices are dependent on both shaft rotation speed and the frequency of excitation.

Because the model is conservative and isotropic, these matrices are symmetrical and are also quasi-diagonal; i.e., the influence coefficients among torsional, lateral forward whirl, and lateral backward whirl degrees of freedom are all zero. At resonant conditions, the mobility matrix is both unbounded and degenerate, all columns are proportional to each other, and because of symmetry all rows are proportional to each other. The stiffness matrix also becomes singular at resonance, but its elements remain finite. These properties are confined to the applicable partitioned submatrices because these submatrices are uncoupled from one another.

4.2 Bearing Support Characteristics

4.2.1 Matrix Representation

The function of a bearing is to restrict the rotor axis to a nominal axis under realistic static and dynamic load environments. Deviation of any particular point of the rotor axis from the nominal line can be characterized by three lineal and two angular displacements. These may be designated as $(\delta_x, \delta_y, \delta_z, s_x, s_y)$ in accordance with a right-handed Cartesian reference system. The z-coordinate is coincident with the reference axis and is directed toward the spin vector. (s_x, s_y) are rotor axis inclinations respectively in the z-x and z-y planes. The x-coordinate is directed toward the predominant static load; e.g., earth gravity. The bearing would resist the occurrence of any displacement so that the reaction force system imparted by the rotor to the bearing is generally expressed in matrix notation as

$$\underline{R} = \underline{Z} \cdot \underline{X}$$

$\underline{R}$ is a column vector comprising the five reaction components $(F_x, F_y, F_z, M_x, M_y)$ while $\underline{X}$ is the displacement vector $(\delta_x, \delta_y, \delta_z, s_x, s_y)$. $\underline{Z}$ is a (5×5) matrix containing the elements Z_{ij} with both indices (i, j) ranging from 1 to 5. The values of Z_{ij} characterize how rotor displacements are being resisted by the bearing.

Ideally it would be desirable to design the bearing such that Z_{ij} is diagonal (e.g., $Z_{ij} = 0$ if $i \neq j$). In reality, some cross-coupling always exists; although it is commonly reasonable to assume independence between the linear (δ_x, δ_y) and the angular (s_x, s_y) as well as between the axial (δ_z) and the transverse (δ_x, δ_y) lineal degrees of freedom. That is:

$$\begin{aligned} Z_{1j} &= Z_{2j} = Z_{j1} = Z_{j2} = 0 \text{ for } j > 2 \\ Z_{3j} &= Z_{j3} = 0 \text{ for } j \neq 3 \end{aligned}$$

Such null conditions are presumed in the present work. That is, cross-coupling exists between δ_x and δ_y and also between s_x and s_y only. The axial characteristics of the bearing support affect only the axial dynamics of the rotor, which are commonly quite benign in comparison with the much more compliant torsional and lateral degrees of freedom. Henceforth, no further attention will be given to the axial motion. Thus, bearing characteristics concern mainly the four lateral degrees of freedom.

Matrix elements Z_{ij} are often dependent on the displacement amplitudes and sometimes also on their time histories. Thus, there are circumstances when rotodynamics is studied by step-by-step numerical integration with respect to time. Although such methods are theoretically more rigorous, they have proven to have only limited usefulness because

- Computational cost consideration precludes execution of such methods except for the simplest mechanical models.
- Stability difficulty associated with numerical integration often masks credibility of such results.

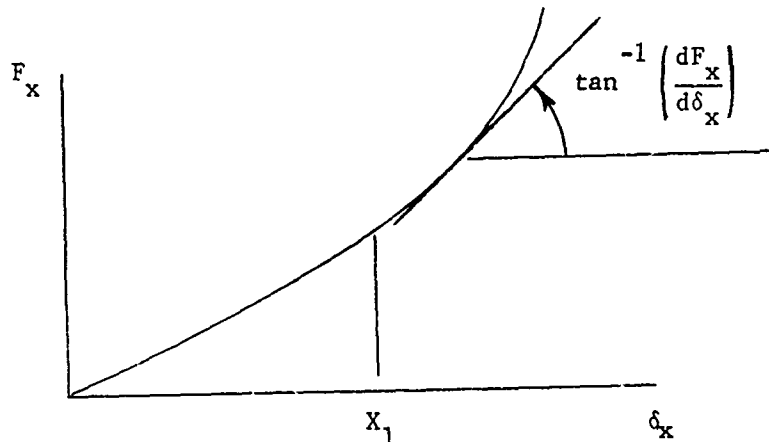
- The method of dynamic perturbation analysis, particularly if one includes the question of stability, has proven to be quite adequate in most realistic engineering problems. Questions of large amplitudes and anomalous histories can be relegated to the qualitative judgment of the experienced rotordynamic expert; in only extremely rare circumstances do such questions require serious consideration.

4.2.2 Linearization

From the standpoint of dynamic perturbation, distinction is made between a static equilibrium component and a dynamic perturbation component for both the displacements and the reactions. Thus,

$$\underline{X} = \underline{X}_0 + \underline{X}'; \quad \underline{F} = \underline{F}_0 + \underline{F}'$$

$(\underline{X}', \underline{F}')$ are respectively presumed to be infinitesimal in comparison with $(\underline{X}_0, \underline{F}_0)$. Accordingly, Z_{ij} are regarded as dependent on $\underline{X}_0$ but not on $\underline{X}'$. To illustrate the idea of perturbation linearization one may examine the one-dimensional load-displacement curve.



According to the illustrated curve, a straight-line relationship appears to be quite adequate for $0 < \delta_x < X_1$. In this range Z_{11} may be regarded as a constant. However, for $\delta_x > X_1$, incremental change of F_x is

$$F'_x = \frac{dF_x}{d\delta_x} \delta'_x$$

where δ'_x is the incremental displacement. $\frac{dF_x}{d\delta_x}$ will depend on

the amplitude of δ_x for $\delta_x > X_1$.

The question of history dependence is circumvented by regarding $\underline{X}'$ as a periodic motion at any frequency ν of interest. The matrix elements Z_{ij} accordingly would have both real and imaginary parts and may also be dependent on both the rotor speed ω and the vibration frequency ν . In effect, the dynamic problems are treated with the frequency domain analysis.

To avoid notational clumsiness, the primes will be dropped from $\underline{F}'$ and $\underline{X}'$ so that $\underline{F}$ and $\underline{X}$ are understood to be dynamic perturbation quantities unless the subscript "0" is used to designate the static equilibrium condition.

4.2.3 Speed Dependence

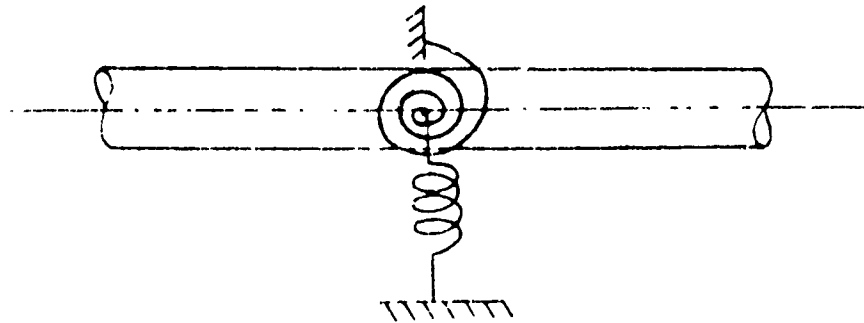
For the two most common bearing types, namely rolling-element and fluid-film bearings, speed is an important parameter.

Fluid-film bearing forces are explicitly proportional to the operating speed. A secondary speed effect is caused by the temperature sensitivity of lubricant viscosity. The effective lubricant viscosity usually decreases since a larger amount of heat is generated at higher speeds.

The deflection of a rolling-element bearing under load is due to the contact compliances at both inner and outer races. At a high operating speed, centrifugal acceleration of the rolling-element increases the contact load at the outer race while the contact with the inner race is accordingly relieved. Since the load-deflection characteristics of race contacts are highly nonlinear, the stiffness of a rolling-element bearing becomes speed dependent.

4.2.4 Dynamic Characterization of Bearing Support

Accurate calculation of the lateral dynamic response of a high speed rotor depends on realistic characterization of the support bearings. In the most general case, both lineal and angular motions are restrained by the support bearings at the attachment location. In the analytical model, the reaction force and the reaction moment of each bearing are felt by the rotor through a single station of the rotor axis. As schematically illustrated below, a coil spring restraining the lateral displacement and a



Bearing Stiffness Model

torsion spring tending to oppose an inclination are attached to the same point of the rotor axis. A complete description of the characteristics of the support bearings, however, involves much more than the specification of the two spring constants. This is because:

- The lateral motion of the rotor axis is associated with two displacement components and two inclination components.
- The restraining characteristics may include cross coupling among various displacement/inclination coordinates.
- The restraining force/moment may not be temporally in phase with the displacement/inclination.
- The restraining characteristics of the bearing may be dependent on either the rotor speed or the frequency of

vibration or both.

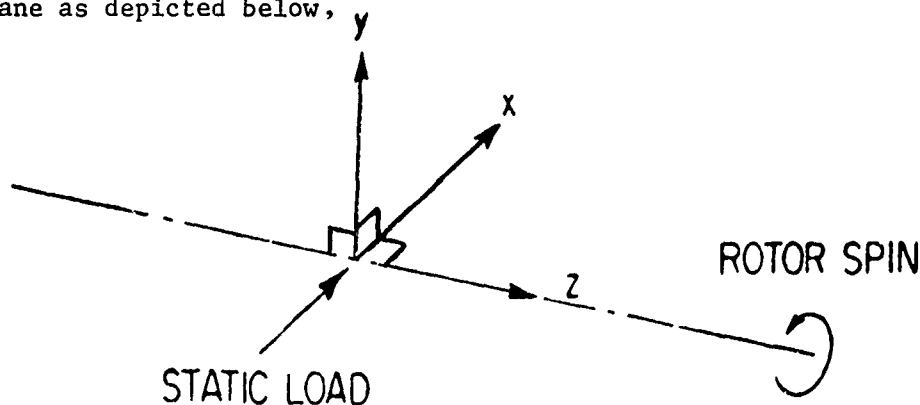
- Bearing pedestal compliance may not be negligible.

To accommodate the above considerations, the support bearing characteristics are described by a four-degrees-of-freedom impedance matrix as defined in the equation

$$\underline{R}_N = \underline{Z}_N \cdot \underline{W}_N$$

where $\underline{W}_N$ is a column vector containing elements which are the two lateral displacements δ_x, δ_y , and the two lateral inclinations s_x, s_y of the rotor axis at the bearing station N.

Employing a right handed Cartesian representation in a lateral plane as depicted below,



Coordinate System

the z-axis is coincident with the spin vector of the rotor. The x-axis is oriented in the direction of the external static load, and the y-axis is perpendicular to both z and x axes forming the right handed triad (x, y, z). δ_x, δ_y are respectively lateral lineal displacement components of the rotor axis along the x, y directions. s_x, s_y are lateral inclination components respectively

in the z-x, z-y planes. Note that s_x is a rotation about the y-axis, while s_y is a rotation about the negative x-axis.

Z_N is a complex 4 X 4 matrix, and, in accordance with the common notation for stiffness and damping coefficients, may be expressed as

$$Z_N = K_N + i\nu B_N$$

where K_N is the stiffness matrix, B_N is the damping matrix, and ν is the frequency of vibration. Most commonly, lateral linear and angular displacements do not interact with each other, so that the non-vanishing portions of K_N and B_N are separate 2 X 2 matrices. That is

$$K_N = \begin{bmatrix} (K_N)_{\text{lineal}} & 0 & 0 \\ & 0 & 0 \\ 0 & 0 & (K_N)_{\text{angular}} \\ 0 & 0 & \end{bmatrix}$$

$$B_N = \begin{bmatrix} (B_N)_{\text{lineal}} & 0 & 0 \\ & 0 & 0 \\ 0 & 0 & (B_N)_{\text{angular}} \\ 0 & 0 & \end{bmatrix}$$

Accordingly, a total characterization of a support bearing would include sixteen coefficients which make up the 4 (2 X 2) matrices:

$$(\underline{K})_{\text{lineal}} = \begin{bmatrix} K_{xx} & K_{xy} \\ K_{yx} & K_{yy} \end{bmatrix}_{\text{lineal}}$$

$$(\underline{B})_{\text{lineal}} = \begin{bmatrix} B_{xx} & B_{xy} \\ B_{yx} & B_{yy} \end{bmatrix}_{\text{lineal}}$$

$$(\underline{K})_{\text{angular}} = \begin{bmatrix} K_{xx} & K_{xy} \\ K_{yx} & K_{yy} \end{bmatrix}_{\text{angular}}$$

$$(\underline{B})_{\text{angular}} = \begin{bmatrix} B_{xx} & B_{xy} \\ B_{yx} & B_{yy} \end{bmatrix}_{\text{angular}}$$

In the event that the pedestal compliance is significant, then the effective support impedance can be calculated from

$$\underline{Z}_N = \left[\underline{Z}_p + (\underline{Z}_b + \underline{Z}_p)^{-1} \cdot \underline{Z}_b \right]_N$$

where subscripts "p" and "b" refer to the pedestal and bearing respectively. Note that both pedestal inertia and damping may be included in $\underline{Z}_p$.

4.2.5 Impedance Alteration

From above discussions, it is clear that an isotropic stiffness representation for a bearing support is a gross simplification. A realistic description of bearing support characteristics should include:

- speed dependence,
- anisotropy or directional sensitivity with respect to the equilibrium load,
- distinction of stiffness and damping elements, and
- cross-coupling effects.

It is, however, not necessary to redo the analysis of a rotor because the representation of the bearing support needs refinement. As shown in Section 5.3.2, for the appropriate degrees-of-freedom associated with the bearing support in question, a direct adjustment of the already-computed impedance matrix suffices. This principle can be used to add any proportional type constraint to the rotor. Therefore, one can conveniently evaluate the characteristics of the rotor system due to

- varied bearing characteristics,
- relocation of bearing support,
- electromagnetic and aerodynamic excitations.

4.3 Natural Modes

4.3.1 Conservative Rotor System

If the bearing damping elements and cross coupling effects are negligible, despite whether or not isotropy is preserved, the rotor system would be conservative. At discrete frequency-speed combinations, self-sustained oscillations are possible. Such conditions are determined as the roots of the impedance determinant. Critical speeds are special cases of the natural modes of a conservative rotor system; the special conditions include restricting the excitation frequency to be in synchronism with shaft rotation and the motion to be in the forward sense of whirl.

4.3.2 Non-Conservative Rotor System

With realistic representation of fluid-film bearing characteristics, the rotor system becomes non-conservative. The natural mode of a non-conservative system can be established in a frequency domain analysis through the concept of system damping. The mathematical analysis required to determine the non-conservative natural modes involves the diagonalization of the impedance matrix, which leads to the formulation of a two-parameter complex eigenvalue problem. Details of the analysis are given in Section 6.2.

The non-conservative natural mode analysis is required to assess potential rotor instabilities which may stem from the improper use of fluid film bearings or the presence of aerodynamic excitations. It is also useful to predict the maximum forced response conditions of both synchronous and asynchronous type and to give an accurate estimate of the amplitudes involved.

4.4 Computational Strategy

In a comprehensive dynamic analysis of a rotor system, the required computation procedure can be logically divided into two steps. The first step concerns the computation of the mobility and impedance

matrices of the idealized structure. The second step deals with the determination of particular dynamic characteristics of the rotor system with the option to include realistic characterization of bearing supports as well as various identifiable excitation sources. Recognition of the logical breakdown of these two steps made it possible to devise a strategy for the computational procedure which is cost effective not only in the tangible sense, but also by providing flexibility to suit the particular needs of the prevailing circumstances. Specifically, efficiency is realized by

- system truncation to omit irrelevant details,
- use of "real" frequency domain analysis for all problem situations,
- judicious use of whirl coordinates, and
- employment of high accuracy interpolation of smooth functions in the frequency domain.

These ideas are amplified separately below.

4.4.1 System Truncation and Active Degrees of Freedom

In the analysis of the rotor structure, if the distributed inertia approach is used for shaft segments, the mathematical representation is inherently truncated. While deflection components can be identified at each intersegmental junction, their distributions along the lengths of the segments are left obscure. For instance, if idealized bearing support characteristics are assumed so that the rotor system is conservative, an infinite number of natural lateral modes can be computed. Since only a finite set of deflection representations is available to describe the various mode shapes, the dimensionality of representation is insufficient and the mode shape description is not unique. This deficiency is not serious, because only a finite number of the lower modes are of practical interest. By heuristic reasoning, one may be convinced that ambiguity in truncated modal representation is

legitimized if the frequency domain is also truncated to limit the total number of natural modes.

This argument can be extended one more step. Since the range of frequency domain of interest is quite readily definable, only a relatively small number of natural modes is of interest. This usually means that there are more than enough inter-segmental junctions to satisfy completeness in modal representation.

System truncation leads to considerable savings of computational cost if the analysis effort goes beyond that for the idealized rotor structure. While reduction of the dimensionality of mode shape representation may enhance computation economy, there are explicit reasons to identify particular locations of the rotor and the particular degree of freedom where dynamic interaction of various type may be of interest. Examples of active degrees of freedom include the following:

Bearing Stations — Isotropic springs represent bearings in the idealized rotor model. In order to allow more realistic characterization of the particular bearing, identification of the corresponding station is necessary so that impedance alteration may be performed. This involves the lateral lineal deflections for a radial bearing and the lateral angular deflection for a thrust bearing.

Alternate Bearing Stations — If the need to consider relocation of bearing support is anticipated, the alternate bearing stations should be identified even though no bearing constraint is assigned there in the idealized rotor model.

Mass Unbalance Station — This is where a mass unbalance type of forcing function is assigned for study of unbalance response.

Gears — For rotors with gears, gear mesh and its harmonic excitation of both lateral and torsional vibrations can

be important. For a spur gear the applicable degrees of freedom are lateral lineal deflections and the torsional twist; the lateral angular deflections are also involved for a bevel gear.

Impellers — Impellers are always potential locations for mass unbalance, there are also possibilities of aerodynamic cross-coupling excitation of shaft whirl. The latter problem can be emulated by assigning equivalent bearing coefficients at the impeller stations.

4.4.2 Frequency Domain Analysis

Use of frequency domain analysis is equivalent to the solution of time-dependent problem by the method of Laplace transformation. The efficacy of this approach for conservative systems is widely accepted, no further elaboration is needed here. By introducing the concept of system damping, non-conservative systems can also be treated. Full details of this method are given in Section 6.2. Both damped response and stability analysis can be accordingly calculated. In the present work, the frequency domain is confined to the real frequency axis. Non-conservative aspects are described in terms of phase shift instead of an exponential coefficient. The well accepted concept of critical damping ratio is suitably defined. Avoidance of the exponential temporal behavior has obvious advantages in computational economy. An additional benefit is its direct correspondence to practical measurements. By and large, experimental data of rotor dynamics pertain to steady-state oscillatory phenomena. Interpretive ease is an important advantage of the frequency response analysis.

4.4.3 Whirl Coordinates

In the analysis of an idealized rotor structure, use of whirl coordinates simplifies the description of gyroscopic inertia and associated computation effort. Even when non-conservative elements are incorporated, it is still advantageous to retain whirl

coordinates in the computation process, so long as isotropy prevails. Verification of isotropy is performed automatically in the computer program so that the simplified computation procedure can be utilized whenever it is permissible.

4.4.4 Interpolation on Impedance Matrices

The computer program allows the user to specify frequencies at which response calculations are desired. Within the specified frequency range, a search is always made to identify natural modes. Since truncated representation reduces the rank of the applicable matrices, interpolation from the available matrices with respect to frequency is likely to be less costly than the execution of a complete calculation cycle at a new frequency. The impedance matrices are used here because its elements always have smoothly varying values. A cubic spline procedure was found to be very effective for this purpose. The cubic spline is described in Appendix B.

SECTION V

FLEXIBLE ROTOR VIBRATION ANALYSIS

This section contains a description of the analytical background in the "structural" treatment of a flexible rotor. The basic approach adopted is patterned after Holzer [17] and Myklestad [18]. The rotor is described in terms of a number of uniform shaft segments which are rigidly attached to each other and share a common geometrical and rotational axis. Rigid body inertia elements can be attached to stations between the shaft segments or at rotor ends. Bearing supports, which affect lateral vibration of the rotor, can also be assigned to intersegmental stations or rotor ends.

It may also be necessary to identify a rotor station for the purpose of recognizing the presence of external forcing or excitation. Most commonly, however, such a station would coincide with the location of a rigid body inertia element. For instance, an aerodynamic excitation would be located at an impeller which calls for a rigid body inertia in the rotor model. Thus, the rotor would be described as a succession of M shaft segments. Accordingly, there are $M + 1$ rotor stations at which rigid body inertia elements, bearing supports, and/or external excitations may be assigned. Shaft segment no. K is enclosed between Stations no. K and $K+1$.* The last shaft segment, no. M , is terminated by Station no. $M+1$.

To allow flexibility in rotor modeling, distinction is made between mass and stiffness diameters. Thus, a complete description of a shaft segment includes:

- l length of shaft segment (in)
- D_i inner stiffness diameter (in)
- D_o outer stiffness diameter (in)
- d_i inner mass diameter (in)
- d_o outer mass diameter (in)

*Station $K+1$ is regarded as being to the right of station K .

- ρ density of shaft material (lb/in³)
- E Young's modulus (psi)
- G shear modulus (psi)

A major departure from the Holzer-Myklestad treatment is the use of distributed analysis of shaft segments. Thus it is not necessary to subdivide a slender and long shaft segment in order to realize accuracy of higher modes. The use of distributed analysis may not always achieve computational economy since it involves transcendental functions. It is preferred because rotor model input setup is simplified and the results are least sensitive to input setup. The distributed analysis makes it easier for the user to achieve good results without extensive modelling experience.

The analysis deals with small displacement periodic motions. The rotor materials are assumed to obey linear elastic constitutive laws. Non-conservative effects, however, can be introduced at bearing support stations. Periodic time dependence is represented by the exponential factor, $e^{i\omega t}$. All variables are allowed to assume complex values, with the absolute value and argument of the complex number giving respectively the amplitude and the temporal phase. Although one cannot directly address the problems of transient motions and limit cycle vibration, most commonly encountered rotor dynamic problems can be treated. The following are state-of-the-art features included to permit an exhaustive analysis of an advanced high speed turbo rotor:

- o The vibration frequency may be different from the rotational speed
- o The bearing support characteristics can include up to 16 coefficients, representing both lineal and angular constraints.
- o The bearing coefficients may be dependent on both rotor speed and vibration frequency. Thus, not only can one study a gas bearing supported rotor, it is also possible to treat the speed dependence of rolling element bearings, speed-frequency dependence of tilting-pad bearings, and to emulate pedestal compliance and inertia.

- o Forced response is automatically calculated at damped resonant frequencies.
- o Rotor system critical damping ratios can be calculated within user specified frequency ranges at all natural modes. When a negative critical damping ratio is encountered, a self-excited instability is indicated.

The analytical formulation is structured to minimize computation cost when calculations are to be repeated many times for the same speed-frequency combinations but with variations of external excitations and bearing support characteristics. Two crucial steps make this possible.

- o A truncated computation system is reduced from the stations of the rotor model. Only such stations, where external excitations are applied and where variations of bearing support characteristics are desired, need be included in the truncated system.
- o A nominal impedance matrix is computed at each speed-frequency combination by inverting the mobility matrix of the truncated system. Variation of bearing support characteristics is achieved by altering specific elements of the nominal impedance matrix without repeating the time-consuming computation of the rotor response from the rotor model.

Due to the small displacement assumption, torsional and lateral vibrations are uncoupled (except that a lateral excitation may simultaneously exert a torsional moment).

In Sections 5.1 and 5.2, computation of torsional and lateral mobility matrices will be separately treated. Also in Section 5.2, the concept of mass unbalance as a rotating excitation is examined. In Section 5.3, various aspects of the system impedance matrix as they are used in rotor dynamic studies are reviewed.

5.1 Torsional Vibration

In a torsional vibration problem, the primitive variables are (ϕ, M_z) , the angle of twist and the torsional moment. ϕ is a continuous function and would be sectionally differentiable with respect to the axial coordinate in each shaft segment, but the derivative, which is proportional to the torsional moment, may be discontinuous across a station at which a lumped polar moment of inertia is attached.

According to the theory of torsion of slender rods [19].

$$M_z = G I_p \frac{d\phi}{dz} \quad (5.1)$$

where, $I_p = \frac{\pi}{32} (D_o^4 - D_i^4)$. Equation (5.1) is applicable in each shaft segment. Using matrix notation, a torsional primitive vector, $\underline{Q}_t$ may be defined to have (ϕ, M_z) as its elements. For shaft segment no. K, one can write $\underline{Q}_t(z_K)$, indicating the dependence of the primitive variables on the local axial coordinate z_K . At either end of the shaft segment, one can define

$$(\underline{Q}_t)_K = \underline{Q}_t(z_K=0); (\underline{Q}_t')_K = \underline{Q}_t(z_K=l_K) \quad (5.2)$$

l_K is the length of the shaft segment no. K.

5.1.1. Calculation at a Station

In the analysis of torsional vibration, the calculation at a station is mainly concerned with the d'Alembert effect of a lumped polar mass moment of inertia. This is described by the matrix equation

$$(\underline{Q}_t)_K = (\underline{T}_{t1})_K \cdot (\underline{Q}_t')_{K-1} \quad (5.3)$$

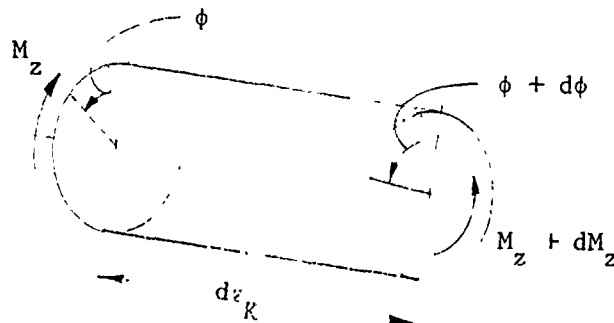
where

$$(\bar{z}_{t1})_K = \begin{bmatrix} 1 & 0 \\ -v^2 I_{pK} & 1 \end{bmatrix} \quad (5.4)$$

I_{pK} is the polar mass moment of inertia at station K.

5.1.2 Calculation Along a Shaft Segment

In a shaft segment, $0 < z_K < \ell_K$, torsional dynamic equilibrium is given by



$$\frac{dM_z}{dz_K} = -v^2 (\rho J_p / g)_K \cdot \phi \quad (5.5)$$

where $J_p = \frac{\pi}{32} (d_o^4 - d_i^4)$ is the cross-sectional polar moment of inertia and g is the gravitational constant (386.4 in/sec^2). Combining with Equation (5.1), one obtains

$$\frac{d^2 \phi}{dz_K^2} = -(\gamma_K v)^2 \phi \quad (5.6)$$

where

$$\gamma_K = \sqrt{\left[\frac{\rho J}{g G I_p} \right]} \quad (5.7)$$

The general solution of Equation (5.6) is

$$\phi = a_1 \cos \gamma_K v z_K + a_2 \sin \gamma_K v z_K$$

Differentiating,

$$\frac{1}{\gamma_K v} \frac{d\phi}{dz_K} = -a_1 \sin \gamma_K v z_K + a_2 \cos \gamma_K v z_K$$

or, in matrix notation, one can write

$$\underline{\phi} = \underline{S}_t(z_K) \cdot \underline{a} \quad (5.8)$$

where,

$$\underline{\phi} = \begin{bmatrix} \phi \\ \frac{1}{\gamma_K v} \frac{d\phi}{dz_K} \end{bmatrix}; \quad \underline{S}_t = \begin{bmatrix} \cos \gamma_K v z_K & \sin \gamma_K v z_K \\ -\sin \gamma_K v z_K & \cos \gamma_K v z_K \end{bmatrix}; \quad \underline{a} = \begin{bmatrix} a_1 \\ a_2 \end{bmatrix} \quad (5.9)$$

Also,

$$\underline{Q}_t = \underline{\sigma}_t \cdot \underline{\phi} \quad (5.10)$$

where

$$\underline{\sigma}_t = \begin{bmatrix} 1 & 0 \\ 0 & (G I_p \gamma)_K v \end{bmatrix} \quad (5.11)$$

Equation (5.8) can be inverted at $z_K = 0$:

$$\underline{a} = \underline{S}_t(0)^{-1} \cdot \underline{\phi}(0) \quad (5.12)$$

Substituting back into Equation (5.8) and setting $z_K = l_K$, one obtains

$$\underline{\phi}(l_K) = \underline{S}_t(l_K) \cdot \underline{S}_t(0)^{-1} \cdot \underline{\phi}(0) \quad (5.13)$$

Now, since

$$(\underline{Q}'_t)_K = \underline{\sigma}_t \cdot \underline{\phi}(l_K)$$

and

$$\underline{\phi}(0) = \underline{\sigma}_t^{-1} \cdot (\underline{Q}_t)_K$$

one can thus rewrite Equation (5.13) as

$$(\underline{Q}')_K = (\underline{T}_{t2})_K \cdot (\underline{Q}_t)_K \quad (5.14)$$

where

$$(\underline{T}_{t2})_K = \left\{ \left[\underline{\sigma}_t \cdot \underline{S}_t(l_K) \cdot \underline{S}_t(0)^{-1} \right] \cdot \underline{\sigma}_t^{-1} \right\}_K \quad (5.15)$$

5.1.3 Torsional Mobility Matrix

Combining Equations (5.3) and (5.14), one obtains

$$(\underline{Q}'_t)_K = (\underline{C}_t)_K \cdot (\underline{Q}'_t)_{K-1} \quad (5.16)$$

where

$$(\underline{C}_t)_K = (\underline{T}_{t2} \cdot \underline{T}_{t1})_K \quad (5.17)$$

$(\underline{C}_t)_K$ is the torsional connection matrix of the primitive vector from the right end of station $K-1$ to the right end of segment K .*

*Station $K+1$ is regarded as being to the right of station K .

The left free end condition is given by

$$(\underline{Q}'_t)_0 = \phi_1 \begin{bmatrix} 1 \\ 0 \end{bmatrix} \quad (5.18)$$

Thus the homogeneous solution for the torsional primitive vector at the left of station $N + 1$ is

$$(\underline{Q}'_t)_{N, \text{ homogeneous}} = \phi_1 \cdot \begin{matrix} N \\ \prod_{K=1} \end{matrix} \begin{matrix} \begin{bmatrix} 1 - \\ 0 - \end{bmatrix} \\ (\underline{C}_{=t})_{N+1-K} \end{matrix} \quad (5.19)$$

If a unit torsional moment is applied at station J , the corresponding particular solution for $N \geq J$ is

$$(\underline{Q}'_t)_{N, \text{ particular}} = \begin{matrix} N+1-J \\ - \prod_{K=1} \end{matrix} \begin{matrix} \begin{bmatrix} - 0 - \\ - 1 - \end{bmatrix} \\ (\underline{C}_{=t})_{N+1-K} \end{matrix} \quad (5.20)$$

For the right end of the shaft, on the right of station $M + 1$, the torsional primitive vector is

$$(\underline{Q}_t)_{M+1} = (\underline{T}_{=t1})_{M+1} \cdot \left\{ \begin{matrix} M \\ \prod_{K=1} \end{matrix} \begin{matrix} \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix} \\ (\underline{C}_{=t})_{M+1-K} \end{matrix} - \begin{matrix} M+1-J \\ \prod_{K=1} \end{matrix} \begin{matrix} \begin{bmatrix} 1 \\ 1 \end{bmatrix} \\ (\underline{C}_{=t})_{M+1-K} \end{matrix} \right\} \quad (5.21)$$

or, writing

$$\begin{aligned}
 (T_{t1})_{M+1} \cdot \prod_{K=1}^M (C_{=t})_{M+1-K} &= \begin{bmatrix} A_{11} & A_{12} \\ A_{21} & A_{22} \end{bmatrix} \\
 (T_{t1})_{M+1} \cdot \prod_{K=1}^{M+1-J} (C_{=t})_{M+1-K} &= \begin{bmatrix} B_{11} & B_{12} \\ B_{21} & B_{22} \end{bmatrix}_J
 \end{aligned} \tag{5.22}$$

then

$$\begin{aligned}
 (Q_t)_{M+1} &= \begin{bmatrix} \phi \\ M_z \end{bmatrix}_{M+1} \\
 &= \phi_1 \begin{bmatrix} A_{11} \\ A_{21} \end{bmatrix} - \begin{bmatrix} B_{12} \\ B_{22} \end{bmatrix}_J
 \end{aligned}$$

Since the right end is free,

$$(M_z)_{M+1} = 0 = \phi_1 A_{21} - (B_{22})_J$$

Therefore,

$$\phi_1 = \frac{(B_{22})_J}{A_{21}} \tag{5.23}$$

Substituting back into Equations (5.19) and (5.20), for $N < J$

$$(Q'_t)_N = \frac{(B_{22})_J}{A_{21}} \prod_{K=1}^N (C_{=t})_{N+1-K} \begin{bmatrix} 1 \\ 0 \end{bmatrix} \tag{5.24a}$$

and for $N \geq J$

$$(\underline{Q}'_t)_N = \frac{(P_{22})_J}{A_{21}} \prod_{K=1}^N (\underline{C})_{N+1-K} \begin{bmatrix} 1 \\ 0 \end{bmatrix} - \prod_{K=1}^{N+1-J} (\underline{C})_{N+1-K} \begin{bmatrix} 0 \\ 1 \end{bmatrix} \quad (5.24b)$$

To obtain the torsional mobility matrix, one must first identify the set of active torsional stations S_t to which J belongs. Equations (5.24) are then used to calculate $(\underline{Q}'_t)_N$ which belong to S_t . The vector of $(\phi)_N$ thus obtained is one column of the torsional mobility matrix corresponding to J .

5.2 Lateral Vibration

The lateral vibration problem is more complicated in many ways:

- o The lateral motion has two degrees of freedom, which are coupled together by gyroscopic inertia, fluid-film bearing effects, and/or forcing functions.
- o It is a fourth order system. Lineal and angular displacements are distinct aspects of the motion. Together with the "internal forces", bending moment and shear force, they form a fourth rank primitive vector. "External force" may be either a lateral moment or a lateral force.
- o Journal bearing characteristics influence lateral vibrations directly.

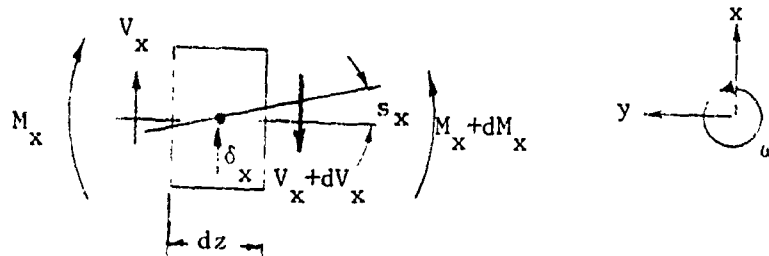
In the Cartesian coordinate system, the lateral lineal motion is described by (δ_x, δ_y) . (x, y, z) form a right-handed triad with the rotational vector of the shaft directed along the z -axis. With the small displacement approximation, the lateral angular displacements are

$$(s_x, s_y) = \frac{d}{dz} (\delta_x, \delta_y) \quad (5.25)$$

According to the flexure theory of slender rods [20], the bending moments and the shear forces in the shaft segment are given by

$$\begin{aligned} (M_x, M_y) &= E I_t \frac{d^2}{dz^2} (\delta_x, \delta_y) \\ (V_x, V_y) &= E I_t \frac{d^3}{dz^3} (\delta_x, \delta_y) \end{aligned} \quad (5.26)$$

where the symbols are defined as follows



and where I_t is the cross-section transverse moment of inertia

$$I_t = \frac{\pi}{64} (D_o^4 - D_i^4) \quad (5.27)$$

For years, it has been known that the flexure theory of slender rods can be improved if shear displacement and rotary inertias are also considered [21]. Such refinements are often proposed to improve calculation accuracy for higher flexural modes. In the study of rotor dynamics, however, such theoretical refinements are overshadowed by our inability to cope with the true conditions at the intersegmental regions. The questions here are concerned with three-dimensional stress fields which are further complicated by assembly and fabrication details such as shrink-fit, flange-bolting, welding, brazing, and/or key-ways. Even with the best available computer codes for three-dimensional elasticity, it is unlikely that these

effects can be treated with sufficient precision to justify improvement of the flexure analysis with shear displacement and rotary inertias.

The potential importance of rotary inertias, however, may also present itself in rigid body-like conical modes. The conventional flexure analysis neglects the cross-sectional rotary inertias and would thus incur inaccuracy in the computation of such modes. This situation can be remedied by adding one half of the cross-sectional rotary inertias of each shaft segment to the intersegmental inertias at either end of the shaft segment.

As indicated previously, gyroscopic inertia would cause coupling between (s_x, s_y) . Thus if the Cartesian coordinate system were to be used to analyze the flexural vibration problem, the two sets of fourth order primitive vectors would have to be carried along simultaneously. Fortunately, gyroscope cross-coupling is of the isotropic type, and by employing forward and backward whirl coordinates, diagonalization of the system can be restored. A brief description of the forward and backward whirl coordinate system is given in Section 5.2.2, subsequent to discussion of lumped lateral inertias in Section 5.2.1, where the gyroscopic phenomenon is treated.

The flexural primitive vectors applicable to shaft segment K in the Cartesian coordinates are

$$\underline{Q}_{fx}(z_K) = \begin{bmatrix} \delta_x \\ s_x \\ M_x \\ V_x \end{bmatrix} ; \quad \underline{Q}_{fy}(z_K) = \begin{bmatrix} \delta_y \\ s_y \\ M_y \\ V_y \end{bmatrix} \quad (5.28)$$

Following the same notation previously used in torsional vibration analysis, the flexural primitive vectors at either end of the Kth segment may be defined as

$$(Q_{fx})_K = Q_{fx} (z_K = 0); (Q'_{fx})_K = Q_{fx} (z_K = l_K)$$

$$(Q_{fy})_K = Q_{fy} (z_K = 0); (Q'_{fy})_K = Q_{fy} (z_K = l_K) \quad (5.29)$$

Similarly, for individual elements of the flexural primitive vectors, one may write

$$(\delta_x)_K = \delta_x (z_K = 0); (\delta'_x)_K = \delta_x (z_K = l_K) \quad (5.30)$$

etc.

Lateral vibrations are affected by bearing supports, the lineal and angular stiffnesses of which respectively cause discontinuities in shear forces and in bending moments. A complete characterization of a bearing support would include damping, cross-coupling, and an-isotropy. These aspects are deferred to Section 5.3.2. In the following nominal bearing support effects are treated in terms of isotropic lineal and angular stiffnesses which are assigned at appropriate stations.

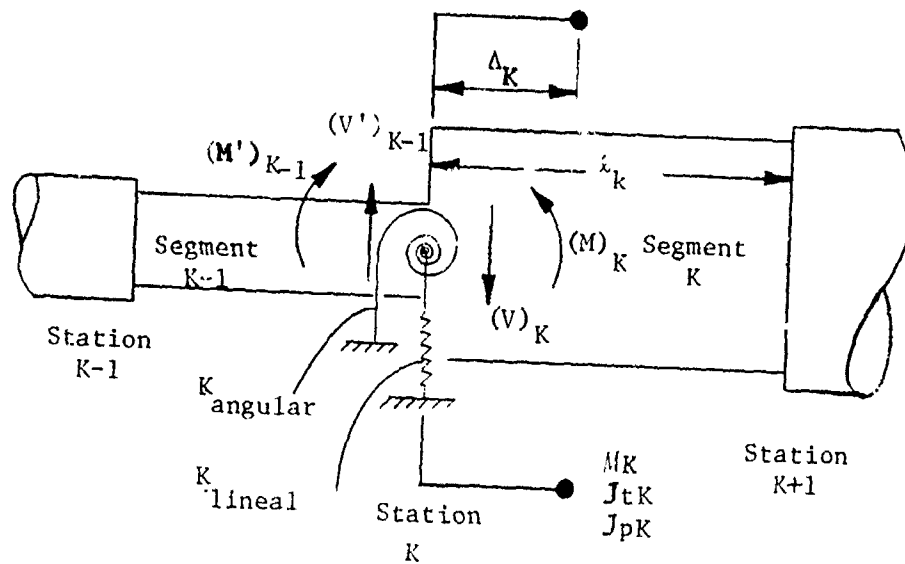
5.2.1 Calculations at a Station

d'Alembert Effects

At a rotor station, a total representation of rigid body inertia would include

- . mass, M_K ;
- . axial offset of c.g., Δ_K , to the right of the station.
- . transverse mass moment of inertia, J_{tK} ; and
- . polar mass moment of inertia, J_{pK}

The location of these inertias is shown in the following sketch.



The polar mass moment of inertia is the same as that used in torsional vibration analysis.

Lineal dynamic equilibrium which accounts for d'Alembert effects, at station K is satisfied by

$$\Delta \begin{bmatrix} (V_x)_K \\ (V_y)_K \end{bmatrix}_{\text{d'Alembert}} = v^2 M_K \left\{ \begin{bmatrix} (\delta_x)_K \\ (\delta_y)_K \end{bmatrix} + \Delta_K \begin{bmatrix} (s_x)_K \\ (s_y)_K \end{bmatrix} \right\} \quad (5.31)$$

Angular dynamic equilibrium is satisfied by

$$\Delta \begin{bmatrix} (M_x)_K \\ (M_y)_K \end{bmatrix} = v^2 M_{K\Delta K} \begin{bmatrix} (\delta_x)_K \\ (\delta_y)_K \end{bmatrix} - \begin{bmatrix} v^2 (J_{tK} + M_K \Delta_K^2) & -i v \omega J_{pK} \\ i v \omega J_{pK} & v^2 (J_{tK} + M_K \Delta_K^2) \end{bmatrix} \begin{bmatrix} (s_x)_K \\ (s_y)_K \end{bmatrix} \quad (5.32)$$

d'Alembert

The off-diagonal elements of the rotary inertia matrix are gyroscopic effects. Detailed derivations are referred to Appendix A. They are responsible for an inherent inertial coupling between the lateral planes for a rotating shaft and cause complications in computation if the Cartesian coordinate system is retained for the lateral motion.

Whirl Coordinates

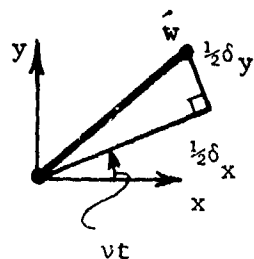
The rotary inertia matrix has identical main diagonal elements, while its off-diagonal elements have the same magnitude but opposite signs. Such a matrix is isotropic and can be diagonalized by using whirl coordinates. The transformation matrix from Cartesian to whirl coordinates is

$$\underline{W} = \frac{1}{2} \begin{bmatrix} 1 & i \\ 1 & -i \end{bmatrix} \quad (5.33)$$

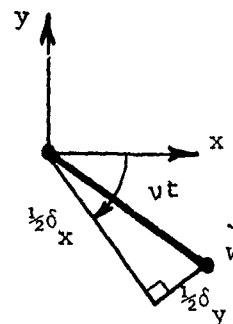
such that the lateral whirl displacements are

$$\begin{bmatrix} \dot{w} \\ w \end{bmatrix} = \underline{W} \begin{bmatrix} \delta_x \\ \delta_y \end{bmatrix} \quad (5.34)$$

$\hat{w}$ represents a forward circular whirl motion while $\check{w}$ is a backward circular whirl motion as illustrated below:



Forward Whirl



Backward Whirl

$\hat{w}$ (" $\wedge$ " designates either a forward or a backward whirl vector) is the amplitude of the circular whirl orbit, while $\text{Arg } \hat{w}$ is the phase advance in the same sense as the respective whirl motion relative to the chosen time reference.

The same transformation applies also to all other vectors in the lateral plane. The inverse whirl transformation is

$$\underline{\underline{W}}^{-1} = \begin{bmatrix} 1 & 1 \\ -i & i \end{bmatrix} \quad (5.35)$$

If $\underline{\underline{A}}$ is an isotropic matrix in the Cartesian coordinate system,

$$\underline{\underline{A}} = \begin{bmatrix} a_1 & a_2 \\ -a_2 & a_1 \end{bmatrix}$$

then its representation in whirl coordinates is

$$\hat{A} = \underline{\underline{W}} \cdot \underline{\underline{A}} \cdot \underline{\underline{W}}^{-1} = \begin{bmatrix} a_1 - ia_2 & 0 \\ 0 & a_1 + ia_2 \end{bmatrix} \quad (5.36)$$

Applying this formula to the rotary inertia matrix in Eq. (5.32), one obtains

$$- \begin{bmatrix} v^2(J_{tK} + M_K \Delta_K^2) - v\omega J_{pK} & 0 \\ 0 & v^2(J_{tK} + M_K \Delta_K^2) + v\omega J_{pK} \end{bmatrix} \quad (5.37)$$

One may observe that, upon transformation into whirl coordinates, the rotary inertia matrix becomes simplified in two ways:

- o off-diagonal terms are eliminated
- o all elements of the matrix are real.

Representation of the lateral motion in whirl coordinates also facilitates its kinematic description. Any simple harmonic motion in the lateral plane describes an elliptical orbit. Use of Equation (5.34) allows one to characterize the elliptical orbit by $(\hat{w}, \check{w})$. Referring to the illustration on the next page, one readily observes:

$$R_1 = \text{Major Orbit Radius} = \left| \hat{w} \right| + \left| \check{w} \right| \quad (5.38)$$

$$R_2 = \text{Minor Orbit Radius} = \left| \hat{w} \right| - \left| \check{w} \right| \quad (5.39)$$

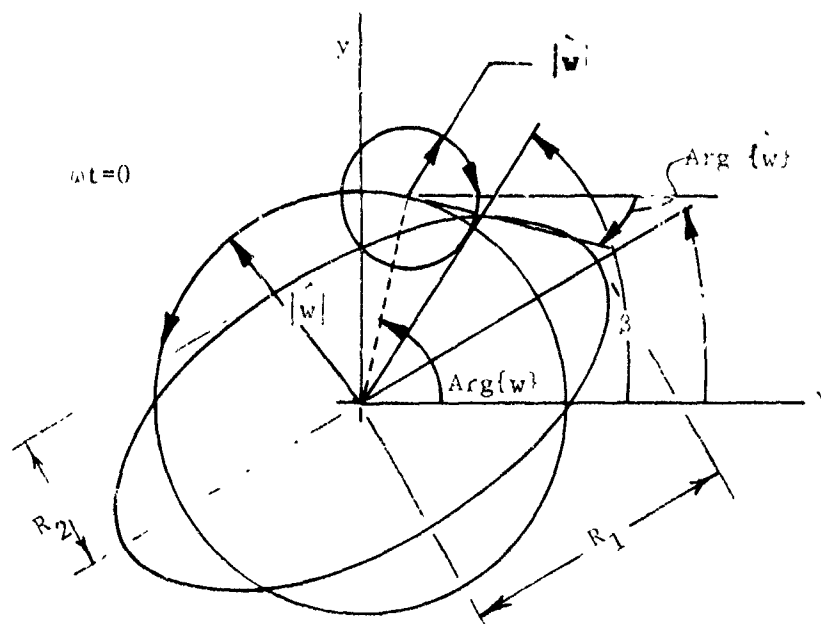
$$\text{Rotational Sense} = S_g \left\{ \left| \hat{w} \right| - \left| \check{w} \right| \right\} \quad (5.40)$$

When the orbit reaches its major axis, the radii of the two counter-rotating motions are coincident; therefore

$$\begin{aligned} \alpha &= \text{Inclination of the major axis} \\ &= vt + \text{Arg } \hat{w} = - \left[vt + \text{Arg } \check{w} \right] \\ &= \frac{1}{2} \left[\text{Arg } \hat{w} - \text{Arg } \check{w} \right] \end{aligned} \quad (5.41)$$

and the polar angular coordinate for the temporal reference, $t = 0$, is

$$\beta = \tan^{-1} \left\{ \frac{\text{Im}(\dot{w} + \ddot{w})}{\text{Re}(\dot{w} + \ddot{w})} \right\} \quad (5.42)$$



Combined Effects of Inertias and Support Stiffnesses

Shear forces and bending moments at a station are also affected by bearing support characteristics, which are represented by isotropic lineal and angular springs here. Combining the effects of inertia elements and springs, the jump condition at station number K can be written in the whirl representation as

$$(\underline{Q}_f)_K = (\underline{T}_{f1})_K \cdot (\underline{Q}_f)_{K-1} \quad (5.43)$$

where

$$(\underline{T}_{f1})_K = \begin{bmatrix} \underline{1} & \underline{0} \\ \underline{M} & \underline{1} \end{bmatrix} \quad (5.44)$$

and

$$\underline{M} = \begin{bmatrix} -v^2 M_{K\Delta K} & -v^2 (J_{tK} + M_{K\Delta K}^2) \pm v\omega J_{pK} + (K_{\text{angular}})_K \\ v^2 M_K - (K_{\text{lineal}})_K & v^2 M_{K\Delta K} \end{bmatrix}$$

5.2.2 Calculations Along a Shaft Segment -- the Dynamical Flexure Solution

The dynamical flexure problem, written in whirl coordinates without rotary inertias and shear deflection is governed by

$$\frac{d\hat{V}}{dz} = v^2 \left(\frac{\rho A}{g} \right) \hat{w} \quad (5.45)$$

Combining with Equations (5.25 and 5.26), one obtains the ordinary differential equation for

$$(EI_t)_K \frac{d^4 \hat{w}}{dz_K^4} = v^2 \left(\frac{\rho A}{g} \right)_K \hat{w} \quad (5.46)$$

and its general solution is

$$\hat{w} = C_1 \cosh \zeta_K z_K + C_2 \sinh \zeta_K z_K + C_3 \cos \zeta_K z_K + C_4 \sin \zeta_K z_K \quad (5.47)$$

where

$$\zeta_K = \left(v^2 \frac{\rho A}{g EI_t} \right)^{\frac{1}{4}} \quad (5.48)$$

Elements in the flexural primitive vector are related to up-to-the-third-order derivatives of $\hat{w}$. Arranging them into a fourth rank column vector, one can write

$$\underline{w} = \underline{S}_f(z_K) \cdot \underline{C} \quad (5.49)$$

where

$$\underline{S}_f = \begin{bmatrix} \cosh \zeta_K z_K & \sinh \zeta_K z_K & \cos \zeta_K z_K & \sin \zeta_K z_K \\ \sinh \zeta_K z_K & \cosh \zeta_K z_K & -\sin \zeta_K z_K & \cos \zeta_K z_K \\ \cosh \zeta_K z_K & \sinh \zeta_K z_K & -\cos \zeta_K z_K & -\sin \zeta_K z_K \\ \sinh \zeta_K z_K & \cosh \zeta_K z_K & \sin \zeta_K z_K & -\cos \zeta_K z_K \end{bmatrix}$$

$$\underline{w} = \begin{bmatrix} \hat{w} \\ \frac{1}{\zeta_K} \frac{d\hat{w}}{dz_K} \\ \frac{1}{\zeta_K^2} \frac{d^2 \hat{w}}{dz_K^2} \\ \frac{1}{\zeta_K^3} \frac{d^3 \hat{w}}{dz_K^3} \end{bmatrix}; \quad \underline{C} = \begin{bmatrix} C_1 \\ C_2 \\ C_3 \\ C_4 \end{bmatrix} \quad (5.50)$$

The flexural primitive vector at the beginning of the shaft segment, $(\underline{Q}_f)_K$, is related to $\underline{w}$ ($z_K = 0$) through scale factors which are associated with (E, I_t, ζ_K) . At the same time, allowance for rotary inertias of one-half the shaft segment can be made in a manner similar to the treatment of lumped inertias at a station. Thus

$$(\underline{T}_{f2})_K \cdot (\hat{\underline{Q}}_f)_K = \underline{\sigma}_f \cdot \underline{S}_f(0) \cdot \underline{C} \quad (5.51)$$

where

$$\begin{aligned}
 (T_{f2})_K &= \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & -\frac{1}{g} \left(\frac{v^2}{2} + v\omega \right) (\rho J_p \ell)_K & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \\
 \sigma_f &= \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \zeta_K & 0 & 0 \\ 0 & 0 & \zeta_K^2 (EI_t)_K & 0 \\ 0 & 0 & 0 & \zeta_K^3 (EI_t)_K \end{bmatrix} \quad (5.52)
 \end{aligned}$$

Similarly,

$$(\hat{Q}'_f)_K = (T_{f2})_K \cdot \sigma_f \cdot S_f(\ell_K) \cdot \underline{C} \quad (5.53)$$

Eliminating $\underline{C}$ between Equations (5.51) and (5.53), one obtains finally

$$(\hat{Q}'_f)_K = \left[T_{f2} \cdot \sigma_f \cdot S_f(\ell_K) \cdot S_f(0)^{-1} \cdot \sigma_f^{-1} \cdot T_{f2} \right]_K \cdot (\hat{Q}_f)_K \quad (5.54)$$

5.2.3 Lateral Mobility Matrix

Combining Equations (5.43) and (5.54), one can write

$$(\hat{Q}'_f)_K = (C_f)_K \cdot (\hat{Q}'_f)_{K-1} \quad (5.55)$$

where

$$(\underline{C}_f)_K = \left[\underline{T}_{f2} \cdot \underline{\sigma}_f \cdot \underline{S}_f(l_K) \cdot \underline{S}_f(0)^{-1} \cdot \underline{\sigma}_f^{-1} \cdot \underline{T}_{f2} \cdot \underline{T}_{f1} \right]_K \quad (5.56)$$

which is the flexural connection matrix of the primitive vector from the left side of station K to the right end of segment K as written in whirl coordinates.

The left free end condition is given by

$$(\hat{Q}'_f)_0 = \hat{w}_1 \begin{bmatrix} 1 \\ 0 \\ 0 \\ 0 \end{bmatrix} + \hat{\theta}_1 \begin{bmatrix} 0 \\ 1 \\ 0 \\ 0 \end{bmatrix} \quad (5.57)$$

Thus the homogeneous solution for the flexural primitive vector at the left of station number N+1 is

$$\begin{aligned} & (\hat{Q}'_f)_N \text{ homogeneous} \\ &= \prod_{K=1}^N (\underline{C}_f)_{N+1-K} \begin{bmatrix} \hat{w}_1 \\ \hat{\theta}_1 \\ 0 \\ 0 \end{bmatrix} \end{aligned} \quad (5.58)$$

If a unit transverse force (in whirl coordinates) is applied at station J, the corresponding particular solution for $N \geq J$ is

$$\begin{aligned} & (\hat{Q}'_f)_N, \text{ particular, force at } J \\ &= \prod_{K=1}^{N+1-J} (\underline{C}_f)_{N+1-K} \begin{bmatrix} 0 \\ 0 \\ 0 \\ 1 \end{bmatrix} \end{aligned} \quad (5.59)$$

Accordingly, for the right end, on the right of station $M+1$, the flexural primitive vector is

$$(\hat{Q}_f)_{M+1}, \text{ force at } J$$

$$= (\hat{T}_{f1})_{M+1} \cdot \left\{ \prod_{K=1}^M (\hat{C}_f)_{M+1-K} \begin{bmatrix} \hat{w}_1 \\ \hat{\theta}_1 \\ 0 \\ 0 \end{bmatrix} + \prod_{K=1}^{M+1-J} (\hat{C}_f)_{M+1-K} \begin{bmatrix} 0 \\ 0 \\ 0 \\ 1 \end{bmatrix} \right\} \quad (5.60)$$

One may write

$$(\hat{T}_{f1})_{M+1} \cdot \prod_{K=1}^M (\hat{C}_f)_{M+1-K} = \begin{bmatrix} A_{11} & A_{12} & A_{13} & A_{14} \\ A_{21} & A_{22} & A_{23} & A_{24} \\ A_{31} & A_{32} & A_{33} & A_{34} \\ A_{41} & A_{42} & A_{43} & A_{44} \end{bmatrix} \text{ flexure}$$

$$(\hat{T}_{f1})_{M+1} \cdot \prod_{K=1}^{M+1-J} (\hat{C}_f)_{M+1-K} = \begin{bmatrix} B_{11} & B_{12} & B_{13} & B_{14} \\ B_{21} & B_{22} & B_{23} & B_{24} \\ B_{31} & B_{32} & B_{33} & B_{34} \\ B_{41} & B_{42} & B_{43} & B_{44} \end{bmatrix} J, \text{ flexure} \quad (5.61)$$

Note, that notations conflicting with Equation (5.22) are used here, therefore annotation "flexure" is used to emphasize the distinction. Since the right end is free,

$$\begin{bmatrix} A_{31} & A_{32} \\ A_{41} & A_{42} \end{bmatrix}_{\text{flexure}} \begin{bmatrix} \hat{w}_1 \\ \hat{\theta}_1 \end{bmatrix}_{\text{force at J}} + \begin{bmatrix} B_{34} \\ B_{44} \end{bmatrix}_{\text{J, flexure}} = 0$$

Or,

$$\begin{bmatrix} \hat{w}_1 \\ \hat{\theta}_1 \end{bmatrix}_{\text{force at J}} = - \begin{bmatrix} A_{31} & A_{32} \\ A_{41} & A_{42} \end{bmatrix}_{\text{flexure}}^{-1} \begin{bmatrix} B_{34} \\ B_{44} \end{bmatrix}_{\text{J, flexure}} \quad (5.62)$$

Substituting back into Equation (5.58), for $N < J$,

$$(\underline{C}_f')_N, \text{ force at J} = - \sum_{K=1}^N (\underline{C}_f)_{N+1-K} \begin{bmatrix} A_{31} & A_{32} \\ A_{41} & A_{42} \end{bmatrix}_{\text{flexure}}^{-1} \begin{bmatrix} B_{34} \\ B_{44} \end{bmatrix}_{\text{J, flexure}} \quad (5.63a)$$

and for $N \geq J$,

$$\begin{aligned}
 & (\hat{Q}'_f)_N, \text{ force at } J \\
 &= - \sum_{K=1}^N (C_f)_{N+1-K} \begin{bmatrix} A_{31} & A_{32}^{-1} \\ A_{41} & A_{42} \end{bmatrix}_{\text{flexure}} \begin{bmatrix} B_{34} \\ B_{44} \end{bmatrix}_J, \text{ flexure} \\
 & \quad + \sum_{K=1}^{N+1-J} (C_f)_{N+1-K} \begin{bmatrix} 0 \\ 0 \\ 0 \\ 1 \end{bmatrix}
 \end{aligned} \tag{5.63b}$$

Similarly, if a unit moment is applied at J , then for $N < J$

$$\begin{aligned}
 & (\hat{Q}'_f)_N, \text{ moment at } J \\
 &= \sum_{K=1}^N (C_f)_{N+1-K} \begin{bmatrix} A_{31} & A_{32}^{-1} \\ A_{41} & A_{42} \end{bmatrix}_{\text{flexure}} \begin{bmatrix} B_{33} \\ B_{43} \end{bmatrix}_J, \text{ flexure} \\
 & \quad + \sum_{K=1}^{N+1-J} (C_f)_{N+1-K} \begin{bmatrix} 0 \\ 0 \\ 0 \\ 1 \end{bmatrix}
 \end{aligned} \tag{5.64a}$$

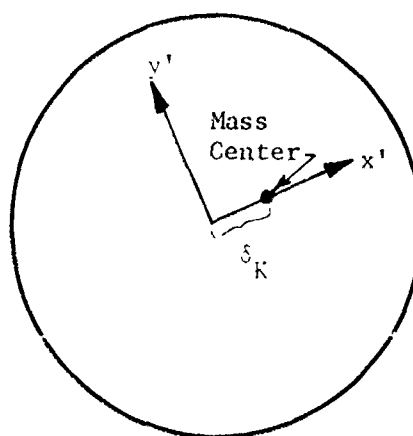
and for $N \geq J$

$$\begin{aligned}
 & (\hat{Q}'_f)_N, \text{ moment at } J \\
 &= \sum_{K=1}^N (C_f)_{N+1-K} \begin{bmatrix} A_{31} & A_{32}^{-1} \\ A_{41} & A_{42} \end{bmatrix}_{\text{flexure}} \begin{bmatrix} B_{33} \\ B_{43} \end{bmatrix}_J, \text{ flexure} \\
 & \quad + \sum_{K=1}^{N+1-J} (C_f)_{N+1-K} \begin{bmatrix} 0 \\ 0 \\ 1 \\ 0 \end{bmatrix}
 \end{aligned} \tag{5.64b}$$

In a flexural system each station may provide either one (w or θ) or two (w and θ) degrees of freedom. Thus, to construct the flexural mobility matrix, one must first identify, S_f , the set of active flexural degrees of freedom to which (w and/or θ)_J belong. Equations (5.63 and/or 5.64) are then used to calculate $(\hat{Q}_f)_N$ for all N which belong to S_f . The array of (w and/or θ)_N thus obtained is the column(s) of the flexural mobility matrix corresponding to the particular degree of freedom at J .

5.2.4 Unbalance Excitation

A common problem in rotor dynamics is the unbalance response. The unbalance problem arises when the center of gravity of a rotor section is not coincident with the axis of rotation. One may elect to describe the situation in terms of a mass moment at the station K , $(M\delta)_K$. The phenomenon of mass unbalance can be understood by studying the rigid-body d'Alembert effects of a rotor section which contains the unbalance mass moment. The chosen coordinate system (x' , y' , z') is fixed to the rotor section with the x' -axis passing through both the cross-sectional reference center, which is the intersection of the cross-section with the nominal rotor axis under a reference static condition, and the mass center.



The instantaneous position vector of the mass center can be expressed according to the parallelogram law as the sum of the position vector pointing to the origin of the body fixed coordinate system and the relative position vector of the mass center in the body-fixed coordinate system; thus

$$\vec{R} = \vec{R}_0 + \delta \vec{R}' \quad (5.65)$$

δ_K measures the shift of the mass center from the cross-sectional reference center

where,

$$\begin{aligned} \vec{R}_0 &= \vec{i}_1 x_1 + \vec{i}_2 x_2 + \vec{i}_3 x_3 \\ \delta \vec{R}' &= \vec{i}_1' \delta_K \end{aligned} \quad (5.66)$$

$(\vec{i}_1', \vec{i}_2', \vec{i}_3')$ are body-fixed unit vectors while $(\vec{i}_1, \vec{i}_2, \vec{i}_3)$ are earth-bound stationary unit vectors. (x, y, z) are components of the instantaneous displacement of the rotor axis. These two sets of unit triads are linearly related to each other through three successive rotational transformations (translational transformation has already been included in $\vec{R}_0$). In matrix notation,

$$\underline{\vec{i}'} = \underline{\Psi} \cdot \underline{\Phi} \cdot \underline{\Theta} \cdot \underline{\vec{i}} \quad (5.67)$$

where

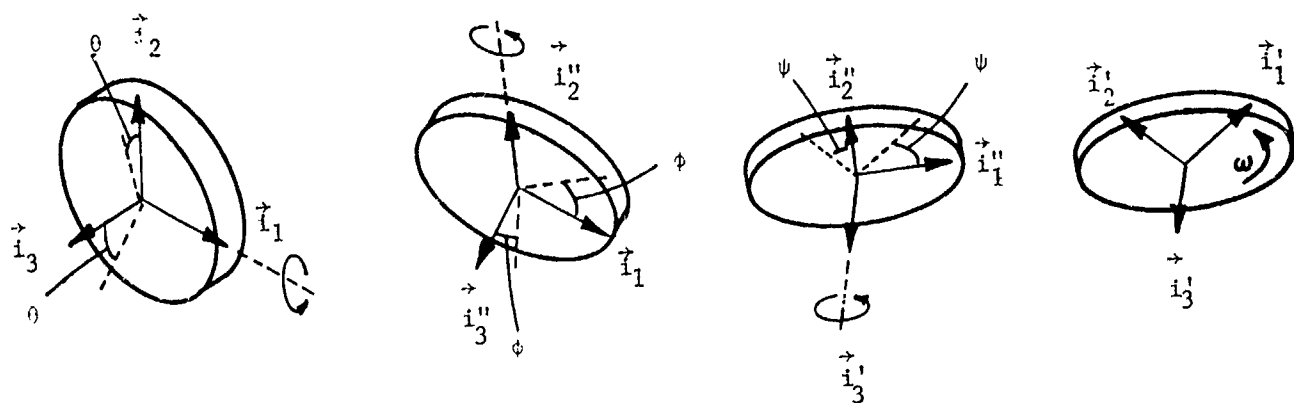
$$\underline{\vec{i}} = \begin{bmatrix} \vec{i}_1 \\ \vec{i}_2 \\ \vec{i}_3 \end{bmatrix}; \quad \underline{\vec{i}'} = \begin{bmatrix} \vec{i}_1' \\ \vec{i}_2' \\ \vec{i}_3' \end{bmatrix} \quad (5.68)$$

$$\underline{\underline{\Theta}} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\theta & \sin\theta \\ 0 & -\sin\theta & \cos\theta \end{bmatrix}$$

$$\underline{\underline{\Phi}} = \begin{bmatrix} \cos\phi & 0 & -\sin\phi \\ 0 & 1 & 0 \\ \sin\phi & 0 & \cos\phi \end{bmatrix}$$

$$\underline{\underline{\Psi}} = \begin{bmatrix} \cos\psi & \sin\psi & 0 \\ -\sin\psi & \cos\psi & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

(5.69)



(θ, ϕ, ψ) are the Euler angles. The geometrical interpretation of Equation (5.67) is illustrated above showing the three steps of rotation transformations:

$$\begin{bmatrix} \vec{i}_1 \\ \vec{i}_2'' \\ \vec{i}_3'' \end{bmatrix} = \underline{\underline{\Theta}} \cdot \begin{bmatrix} \vec{i}_1 \\ \vec{i}_2 \\ \vec{i}_3 \end{bmatrix}; \quad \begin{bmatrix} \vec{i}_1'' \\ \vec{i}_2'' \\ \vec{i}_3'' \end{bmatrix} = \underline{\underline{\Phi}} \cdot \begin{bmatrix} \vec{i}_1' \\ \vec{i}_2'' \\ \vec{i}_3'' \end{bmatrix}; \quad \begin{bmatrix} \vec{i}_1' \\ \vec{i}_2' \\ \vec{i}_3' \end{bmatrix} = \underline{\underline{\Psi}} \cdot \begin{bmatrix} \vec{i}_1'' \\ \vec{i}_2'' \\ \vec{i}_3'' \end{bmatrix}$$

(5.70)

For small flexural deflections, (θ, ϕ) are regarded as infinitesimal angles. Time-derivatives of $\vec{i}$ can be expressed in terms of time-derivatives of (θ, ϕ, ψ) ; that is

$$\dot{\vec{i}} = (\dot{\underline{\psi}} \cdot \underline{\phi} \cdot \underline{\theta} + \underline{\psi} \cdot \dot{\underline{\phi}} \cdot \underline{\theta} + \underline{\psi} \cdot \underline{\phi} \cdot \dot{\underline{\theta}}) \cdot \vec{i} \quad (5.71)$$

where

$$\begin{aligned} \dot{\underline{\theta}} &= \begin{bmatrix} 0 & 0 & 0 \\ 0 & -\sin\theta & \cos\theta \\ 0 & -\cos\theta & -\sin\theta \end{bmatrix} \dot{\theta} \\ \dot{\underline{\phi}} &= \begin{bmatrix} -\sin\phi & 0 & -\cos\phi \\ 0 & 0 & 0 \\ \cos\phi & 0 & -\sin\phi \end{bmatrix} \dot{\phi} \\ \dot{\underline{\psi}} &= \begin{bmatrix} -\sin\psi & \cos\psi & 0 \\ -\cos\psi & -\sin\psi & 0 \\ 0 & 0 & 0 \end{bmatrix} \dot{\psi} \end{aligned} \quad (5.72)$$

Equation (5.67) can be inverted:

$$\vec{i} = \underline{\underline{\theta}}^{-1} \cdot \underline{\underline{\phi}}^{-1} \cdot \underline{\underline{\psi}}^{-1} \cdot \vec{i}', \quad (5.73)$$

Substituting into Equation (5.71), one obtains

$$\begin{aligned} \dot{\vec{i}} &= (\dot{\underline{\underline{\psi}}} \cdot \underline{\underline{\psi}}^{-1} + \underline{\underline{\psi}} \cdot \dot{\underline{\underline{\phi}}} \cdot \underline{\underline{\phi}}^{-1} \cdot \underline{\underline{\psi}}^{-1} + \underline{\underline{\psi}} \cdot \underline{\underline{\phi}} \cdot \dot{\underline{\underline{\theta}}} \cdot \underline{\underline{\theta}}^{-1} \cdot \underline{\underline{\phi}}^{-1} \cdot \underline{\underline{\psi}}^{-1}) \cdot \vec{i}' \\ &= \begin{bmatrix} 0 & \omega'_3 & -\omega'_2 \\ -\omega'_3 & 0 & \omega'_1 \\ \omega'_2 & -\omega'_1 & 0 \end{bmatrix} \cdot \vec{i}' \end{aligned} \quad (5.74)$$

where,

$$\begin{aligned}\omega_1' &= \dot{\theta} \cos\phi \cos\psi + \dot{\phi} \sin\psi \\ \omega_2' &= -\dot{\theta} \cos\phi \sin\psi + \dot{\phi} \cos\psi \\ \omega_3' &= \dot{\theta} \sin\phi + \dot{\psi}\end{aligned}\quad (5.75)$$

and

$$\ddot{\underline{i'}} = \left\{ \begin{bmatrix} 0 & \dot{\omega}_3' & -\dot{\omega}_2' \\ -\dot{\omega}_3' & 0 & \dot{\omega}_1' \\ \dot{\omega}_2' & -\dot{\omega}_1' & 0 \end{bmatrix} + \begin{bmatrix} -\omega_3'^2 - \omega_2'^2 & \omega_1' \omega_2' & \omega_3' \omega_1' \\ \omega_1' \omega_2' & -\omega_3'^2 - \omega_1'^2 & \omega_2' \omega_3' \\ \omega_3' \omega_1' & \omega_2' \omega_3' & -\omega_1'^2 - \omega_2'^2 \end{bmatrix} \right\} \cdot \underline{i'} \quad (5.76)$$

where,

$$\begin{aligned}\ddot{\omega}_1' &= \ddot{\theta} \cos\phi \cos\psi + \ddot{\phi} \sin\psi - \dot{\theta} \dot{\phi} \sin\phi \cos\psi + \dot{\phi} \dot{\psi} \cos\psi - \dot{\psi} \dot{\theta} \cos\phi \sin\psi \\ \ddot{\omega}_2' &= -\ddot{\theta} \cos\phi \sin\psi + \ddot{\phi} \cos\psi + \dot{\theta} \dot{\phi} \sin\phi \sin\psi - \dot{\phi} \dot{\psi} \sin\psi - \dot{\psi} \dot{\theta} \cos\phi \cos\psi \\ \ddot{\omega}_3' &= \ddot{\theta} \sin\phi + \ddot{\psi} + \dot{\theta} \dot{\phi} \cos\phi\end{aligned}\quad (5.77)$$

If flexural displacements are small, (θ, ϕ) are regarded to be infinitesimal. Then Equations (5.75) are reduced to:

$$\begin{aligned}\omega_1' &\approx \dot{\theta} \cos\psi + \dot{\phi} \sin\psi \\ \omega_2' &\approx -\dot{\theta} \sin\psi + \dot{\phi} \cos\psi \\ \omega_3' &\approx \dot{\psi}\end{aligned}\quad (5.78)$$

Accordingly, neglecting second order infinitesimal terms,

$$\ddot{\underline{i'}} \approx \left\{ \begin{bmatrix} 0 & \dot{\omega}_3' & -\dot{\omega}_2' \\ -\dot{\omega}_3' & 0 & \dot{\omega}_1' \\ \dot{\omega}_2' & -\dot{\omega}_1' & 0 \end{bmatrix} + \begin{bmatrix} -\omega_3'^2 & 0 & \omega_3' \omega_1' \\ 0 & -\omega_3'^2 & \omega_2' \omega_3' \\ -\omega_3' \omega_1' & \omega_2' \omega_3' & 0 \end{bmatrix} \right\} \cdot \underline{i'} \quad (5.79)$$

and

$$\begin{aligned}\dot{\omega}_1' &= \ddot{\theta} \cos\psi + \ddot{\phi} \sin\psi + \dot{\phi}\dot{\psi}\cos\psi \\ \dot{\omega}_2' &= -\ddot{\theta} \sin\psi + \ddot{\phi} \cos\psi - \dot{\psi}\dot{\theta}\cos\psi \\ \dot{\omega}_3' &= \dot{\psi}\end{aligned}\quad (5.80)$$

The d'Alembert force can thus be obtained by taking the second time derivatives of Equations (5.65) and (5.66):

$$\begin{aligned}-M\ddot{\vec{R}} &= -M(\ddot{\vec{R}}_0 + \ddot{\vec{S}}\vec{R}') \\ &= -M\ddot{\vec{R}}_0 - \ddot{\vec{I}}_1' M\delta_k\end{aligned}$$

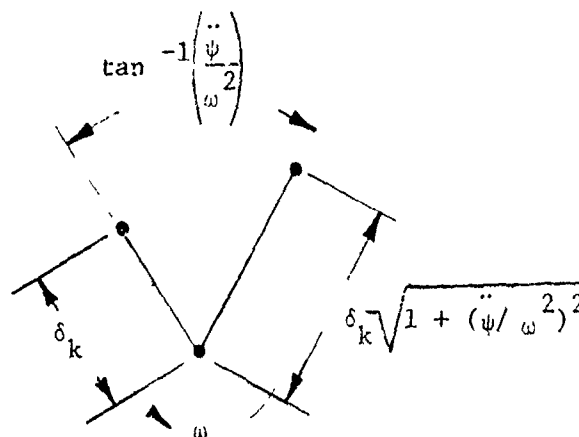
And, making use of Equations (5.79) and (5.80),

$$\begin{aligned}-M\ddot{\vec{R}} &= -M\ddot{\vec{R}}_0 - M\delta_k \{-\ddot{\vec{I}}_1' (\dot{\psi})^2 + \ddot{\vec{I}}_2' \ddot{\psi} + \ddot{\vec{I}}_3' (\ddot{\theta} \sin\psi - \ddot{\phi} \cos\psi \\ &\quad + 2\dot{\psi}\dot{\theta}\cos\psi + 2\dot{\psi}\dot{\phi}\sin\psi)\}\end{aligned}\quad (5.81)$$

In an ideal situation, all sections of the rotor would be perfectly balanced so that $\delta_k = 0$. Furthermore, in the absence of other forms of vibrational excitation, $(|\vec{R}_0|, \theta, \phi) = 0$ and $\dot{\psi} = \omega = \text{constant}$ is the rotational angular speed. The dominant effect of the unbalance response problem is measured by the magnitude $M\delta_k\omega^2$. Constancy of $\dot{\psi}$ would be perturbed by rotor acceleration and/or torsional vibration. Ordinarily, both are secondary effects. The rate of angular acceleration usually is small in comparison with the rate of rotation and the torsional twist is generally a small quantity. Thus, one may write $\dot{\psi} = \omega + \delta\dot{\psi}$, $\delta\dot{\psi}$ being the "rotational rate perturbation". $(\delta\psi, \delta\theta, \delta\phi)$ are regarded as first order perturbations. Equation (5.81) can thus be reduced to

$$-M\ddot{\vec{R}} = -M\ddot{\vec{R}}_0 + \ddot{\vec{I}}_1' M\delta_k \omega^2 \quad (5.82)$$

$-M \ddot{R}_0$ is the d'Alembert force which is already included in the lateral vibration analysis. Since $\vec{I}_1$ is fixed with the rotor cross section, $\vec{I}_1 M \delta_k \omega^2$ represents the unbalance excitation in the form of a centrifugal force, which has a constant amplitude and is revolving synchronously. Thus, one may conveniently use the whirl coordinate system as described in Section 5.2.1. The unbalance excitation would be represented by the constant $M \delta_k \omega^2$ as a forward whirling force. If unbalances at different axial locations are in various radial planes, a complex number would be used; the amplitude would be the magnitude of the centrifugal force, and the argument would indicate the angular orientation of the unbalance measured from a suitable reference in the same sense as the rotation vector. One may observe from Equation (5.81) that acceleration of the rotor, $(-\vec{I}_2 M \delta_k \ddot{\psi})$, would appear as a lag component as illustrated below.



With acceleration, the apparent phase angle is

$$-\tan^{-1} \left(\frac{\ddot{\psi}}{\omega^2} \right) \quad (5.83)$$

and the apparent amplitude is enlarged by the factor

$$\{ (\ddot{\psi})^2 + \omega^4 \}^{1/2} / \omega^2 \quad (5.84)$$

When processing unbalance response data during acceleration or deceleration, compensation for these effects may be necessary.

5.3 Impedance Matrix

5.3.1 Combined Isotropic Matrices

In Section 5.1 it is shown that a linear relationship exists between the angle of twist at station m , ϕ_m , and an externally applied torsional moment at station n , $M_{z,n}$, at any oscillation frequency ν . This can be written in the matrix notation as

$$\underline{\phi} = \underline{A}_{\text{torsion}} \cdot \underline{M}_z \quad (5.85)$$

$\underline{A}_{\text{torsion}}$ is a square matrix, the elements of which may be dependent on ν . Since the torsional vibration problem concerns a conservative system, $\underline{A}_{\text{torsion}}$ is symmetrical in accordance with the classical theory of mechanics. $\underline{\phi}$ and $\underline{M}_z$ are column vectors, the elements of which respectively designate the angles of twist and applied torsional moments at various stations of interest.

The analogous flexure problem was described in Section 5.2. The motion at each rotor station for a flexure problem consists of four degrees of freedom. The flexure motion may have components in either of two lateral orthogonal planes. As shown in Section 5.2.1, due to the gyroscopic effect, it is more convenient to use whirl coordinates to represent the flexural motion instead of the more conventional Cartesian coordinates associated with the lateral planes. For either the forward or the backward whirl component, the flexural motion at station m is described by both a deflection $\hat{w}_m$ and an inclination, $\hat{\theta}_m$. External flexural excitation at station n can be similarly represented in whirl coordinates and consists of both a lateral force, $\hat{F}_n$ and a lateral moment, $\hat{M}_n$. The applicable matrix equation is

$$\underline{W} = \underline{A}_{\text{flexure}} \cdot \underline{F} \quad (5.86)$$

$\underline{W}$, which describes the flexural motion, is a column vector of an even rank. The upper and lower halves of $\underline{W}$ respectively represent the forward and backward whirl components. At each station, for either the forward or the backward whirl component, the deflection and the inclination make up a pair of elements of the $\underline{W}$ vector. Thus the contents of $\underline{W}$ are $(\hat{w}_1, \hat{\theta}_1, \dots; \check{w}_2, \check{\theta}_2, \dots)$. $\underline{F}$ is a column vector describing the flexural excitations. The elements of $\underline{F}$ are the lateral force and moment of either whirl component. Since the rotor structure is symmetrical and bearing supports are approximated by isotropic springs, the forward and backward whirl motions are uncoupled. Thus, $\underline{A}_{\text{flexure}}$ is empty in the off-diagonal half partitions and can be expressed as

$$\underline{A}_{\text{flexure}} = \begin{bmatrix} \underline{\hat{A}} & \underline{0} \\ \underline{0} & \underline{\check{A}} \end{bmatrix} \quad (5.87)$$

$\underline{\hat{A}}$ and $\underline{\check{A}}$ are of half rank. Since the flexure problem (with bearing supports approximated by isotropic springs) is also conservative, $\underline{\hat{A}}$ and $\underline{\check{A}}$ are both symmetrical. $\underline{\phi}$ and $\underline{W}$ can be put together to form a generalized displacement vector $\underline{x}$, and correspondingly, $\underline{M_z}$ and $\underline{F}$ would be put together to form the generalized force vector $\underline{P}$.

If $\underline{\phi}$ and $\underline{W}$ contain only elements which are identified with stations of the rotor, then Equations (5.85) and (5.86) are actually truncated representations of the physical system as computed by the procedures outlined in Sections 5.1 and 5.2. Suppose there are N shaft segments, then there are $N+1$ stations. The rank of $\underline{\phi}$ is $N+1$ while that of $\underline{W}$ is $4(N+1)$. Due to the distributed method of analysis of the shaft segments, the number of free modes which can be calculated accurately is unlimited. In contrast, with a lumped parameter analysis [22], mass effects are assigned as rigid bodies at the stations while shaft segments are regarded as massless torsion/flexure springs; accordingly, one can only calculate $N+1$ torsional modes and $4(N+1)$ flexural modes. Actually, the accuracy of the higher modes as computed by the latter

method is questionable; one ordinarily would accept only about the lower 1/3 modes as accurately calculated.

Truncation can be carried out further by omitting some stations altogether, and/or by leaving out one of the two flexure motion parameters (deflection and inclination), and/or by disregarding the backward whirl motion if the rotor system is known to be isotropic while the excitation is a pure forward whirl (e.g., unbalance). In addition, torsional and flexural problems are usually separately treated. For example, suppose there are 10 rotor stations but only the following degrees of freedom are considered to be active,

<u>Active Station Number</u>	
Torsion	2,9
Deflection	1,2,6
Inclination	2,9

and that whirls in both senses are of interest; then the generalized displacement vector is

$$\underline{x} = \begin{bmatrix} \phi_2 \\ \phi_9 \\ w_1 \\ w_2 \\ \theta_2 \\ w_6 \\ \theta_9 \\ w_1 \\ w_2 \\ \theta_2 \\ w_6 \\ \theta_9 \end{bmatrix} \quad (5.88)$$

The total rank of this formulation is reduced to 12 from the maximum possible rank of 50. The major motivation for rank reduction by truncation is to achieve computation economy. One should retain only sufficient active stations and/or degrees of freedom in order to describe the mode shapes in sufficient detail and to allow consideration of various engineering considerations such as:

- Balancing corrections,
- Bearing support variations,
- Bearing relocations,
- Aerodynamic excitation,
- Wheel shroud rubbing, and
- Geared coupling of rotors.

Regardless of the extent of truncation, a conservative isotropic rotor system can be represented by the combined matrix equation

$$\underline{X} = \underline{A} \cdot \underline{P} \quad (5.89)$$

where,

$$\underline{X} = \begin{bmatrix} \underline{\phi} \\ \underline{W} \\ \underline{W} \end{bmatrix}; \quad \underline{P} = \begin{bmatrix} \underline{M_z} \\ \underline{F} \\ \underline{F} \end{bmatrix} \quad (5.90)$$

And the $\underline{A}$ matrix (commonly known as influence or mobility matrix) is quasi-diagonal; that is,

$$\underline{A} = \begin{bmatrix} \underline{A}_{\text{torsion}} & \underline{0} & \underline{0} \\ \underline{0} & \underline{A} & \underline{0} \\ \underline{0} & \underline{0} & \underline{A} \end{bmatrix} \quad (5.91)$$

$\underline{A}_{\text{tors}}$, $\underline{A}$ and $\underline{A}$ are all symmetrical. Upon inversion, one obtains

$$\underline{P} = \underline{K} \cdot \underline{X} \quad (5.92)$$

where,

$$\underline{\underline{K}} = \begin{bmatrix} \underline{\underline{K}}_{\text{torsion}} & \underline{\underline{0}} & \underline{\underline{0}} \\ \underline{\underline{0}} & \underline{\underline{K}} & \underline{\underline{0}} \\ \underline{\underline{0}} & \underline{\underline{0}} & \underline{\underline{K}} \end{bmatrix}$$

$$\underline{\underline{K}}_{\text{torsion}} = \underline{\underline{A}}_{\text{torsion}}^{-1}; \quad \underline{\underline{K}} = \underline{\underline{A}}^{-1}; \quad \underline{\underline{K}} = \underline{\underline{A}}^{-1} \quad (5.93)$$

$\underline{\underline{K}}$ is known as the stiffness or impedance matrix.

5.3.2 Study of Bearing Effects - Impedance Alteration

Representation of a bearing support by an isotropic spring, together with the use of whirl coordinates, allows considerable simplification in the computation of $\underline{\underline{A}}_{\text{flexure}}$ and its inversion to obtain $\underline{\underline{K}}_{\text{flexure}}$ in two ways:

- All elements of $\underline{\underline{A}}_{\text{flexure}}$ are real.
- $\underline{\underline{A}}_{\text{flexure}}$ is empty in its off-diagonal half partitions.

However, fluid film bearings, which are in increasing use in modern rotating machines, are commonly described by eight coefficients*. Thus, in Cartesian coordinates, reactions of a fluid film bearing to lateral displacements are expressed as

$$\begin{bmatrix} F_x \\ F_y \end{bmatrix}_{\text{brg}} = - \begin{bmatrix} K_{xx} + i\nu B_{xx} & K_{xy} + i\nu B_{xy} \\ K_{yx} + i\nu B_{yx} & K_{yy} + i\nu B_{yy} \end{bmatrix} \begin{bmatrix} \delta_x \\ \delta_y \end{bmatrix} \quad (5.94)$$

* The equation governing fluid film journal bearings is self-adjoint with respect to squeeze-film motion. Therefore, $B_{xy} = B_{yx}$ generally holds.

Upon transforming to whirl coordinates according to the procedure outlined in Section 5.2.1, this becomes

$$\begin{bmatrix} \hat{F} \\ \hat{F} \end{bmatrix}_{\text{brg}} = \begin{bmatrix} Z_{||} - iZ_{\perp} & \Delta Z_{||} + i\Delta Z_{\perp} \\ \Delta Z_{||} - i\Delta Z_{\perp} & Z_{||} + iZ_{\perp} \end{bmatrix} \begin{bmatrix} \hat{W} \\ \hat{W} \end{bmatrix} \quad (5.95)$$

where

$$\begin{aligned} Z_{||} &= \frac{1}{2} \{ (K_{xx} + K_{yy}) + i\nu(B_{xx} + B_{yy}) \} \\ \Delta Z_{||} &= \frac{1}{2} \{ (K_{xx} - K_{yy}) + i\nu(B_{xx} - B_{yy}) \} \\ Z_{\perp} &= \frac{1}{2} \{ (K_{xy} - K_{yx}) + i\nu(B_{xy} - B_{yx}) \} \\ \Delta Z_{\perp} &= \frac{1}{2} \{ (K_{xy} + K_{yx}) + i\nu(B_{xy} + B_{yx}) \} \end{aligned} \quad (5.96)$$

If one recognizes that the matrix of Equation (5.95) should replace the stiffness coefficients of an isotropic spring, then one can write, for the particular station in concern

$$\begin{bmatrix} \hat{F} \\ \hat{F} \end{bmatrix}_{\text{isotropic spring}} = \begin{bmatrix} \hat{F} \\ \hat{F} \end{bmatrix}_{\text{actual}} = \begin{bmatrix} Z_{||} - k - iZ_{\perp} & \Delta Z_{||} + i\Delta Z_{\perp} \\ \Delta Z_{||} - i\Delta Z_{\perp} & Z_{||} - k + iZ_{\perp} \end{bmatrix} \begin{bmatrix} \hat{W} \\ \hat{W} \end{bmatrix} \quad (5.97)$$

Upon substituting this relation into Equation (5.92) and regrouping, one finds

$$K_{\text{flexure}} = \begin{bmatrix} \frac{K}{\rho} & 0 \\ 0 & \frac{K}{\rho} \end{bmatrix} + K_{\text{alteration}} \quad (5.98)$$

to be the flexure impedance matrix with the actual bearing characteristics.

If, for instance, such an alteration is applicable to station 2 of Equation (5.88), then

$\underline{K}_{\text{alteration}}$

$$= \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & Z_{||} - k - iZ_{\perp} & 0 & 0 & 0 & 0 & \Delta Z_{||} + i\Delta Z_{\perp} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & \Delta Z_{||} - i\Delta Z_{\perp} & 0 & 0 & 0 & 0 & Z_{||} - k + iZ_{\perp} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix} \quad (5.99)$$

By such a procedure, the influence of varying bearing characteristics can be studied without repeating the computations described in Section 5.2.

It should be clear that since the alteration procedure can subtract from one station the stiffness which was originally assigned to it in computing the original isotropic mobility matrix and add some stiffness to another station, so long as both stations have been identified as active stations, one can evaluate the effects of relocating bearings quite conveniently.

5.3.3 Scaling of Impedance Matrix

Each diagonal element of the impedance matrix is roughly the linear combination of stiffness, inertia, and damping effects associated with the portion of rotor near the junction represented by the matrix element. In typical problems, the numerical value of the matrix element can be quite large, it is not uncommon to be in excess of 10^6 . The determinant of the impedance matrix is then of the order of $(10^6)^N$, N being the rank of the matrix. Even in a truncated representation, several junctions would be identified as active degrees of freedom; for the lateral vibration analysis of an anisotropic rotor the rank of the matrix would be twice the number of active junctions. For instance, if four junctions are active, N would be eight. Thus, computation of the determinant of the impedance matrix, which is done repeatedly in treating the eigenvalue problems, very large numbers, in excess of 10^{48} , are encountered. This situation readily causes difficulty of exponent overflow in numerical computation. The problem is proportionally more serious when higher modes are treated. Rescaling of the impedance matrix is therefore necessary to ensure trouble-free computation. A suitable rescaling procedure is to divide each element of the impedance matrix by the square of the excitation frequency (frequency is measured in radians/sec here). By so doing, a diagonal element is converted to a mass from inertia. Its range of numerical value then becomes bounded within very reasonable limits.

SECTION VI

EIGENVALUE PROBLEMS

6.1 Diagonalization of the Impedance Matrix

Given the impedance matrix $\underline{K}$, which may contain the actual bearing characteristics, one may pose the question whether or not one can find the condition

$$\underline{K} \cdot \underline{x} = \kappa \underline{x} \quad (6.1)$$

This equation indicates that premultiplication of the displacement vector, $\underline{x}$, results in the uniform "complication" of all elements by the same factor κ . It can be rewritten as

$$(\underline{K} - \kappa \underline{I}) \cdot \underline{x} = 0 \quad (6.2)$$

where $\underline{I}$ is the identity matrix. In the last form, one is confronted with a linear homogeneous system for which the only non-trivial solution is satisfied by the condition

$$|\underline{K} - \kappa \underline{I}| = 0 \quad (6.3)$$

Only discrete values of $\kappa = \kappa_\alpha$ can satisfy Equation (6.3). Associated with each κ_α is the modal vector $\underline{x}_\alpha$, which together with κ_α satisfies Equation (6.1). The homogeneous nature of Equation (6.2) makes the amplitude of $\underline{x}_\alpha$ an indeterminate quantity. A common normalization condition is to equate the largest element of $\underline{x}_\alpha$ to unity. Since $\underline{K}$ is dependent on the frequency of motion, ν , κ_α and $\underline{x}_\alpha$ are thus also frequency dependent. The mathematical problem outlined above is known as an eigenvalue problem. Equation (6.3) is the eigenvalue or characteristic value equation; the roots of which, κ_i , are the eigenvalues, and $\underline{x}_i$ are the eigenvectors or modal vectors.

6.2 Pseudo Single-Degree-of-Freedom Concepts

κ_α in general can be a complex quantity, hence one can write

$$\kappa_\alpha(\nu) = u_\alpha(\nu) + i v_\alpha(\nu) \quad (6.4)$$

Substituting Equations (6.1) and (6.4) into Equation (6.2), one obtains

$$\underline{P}_\alpha = (u_\alpha + i v_\alpha) \underline{x}_\alpha \quad (6.5)$$

which may be regarded as the modal force. Of special interest is the condition

$$u_\alpha(v_\alpha) = 0 \quad (6.6)$$

which defines the natural frequency v_α at which $\underline{x}_\alpha$ could be self-sustained provided $v_\alpha(v_\alpha)$ also vanishes. If $v_\alpha(v_\alpha)$ does not vanish, then its sign indicates whether $\underline{P}_\alpha$ would be providing energy to the rotor system if $v_\alpha > 0$, or $\underline{P}_\alpha$ would be removing energy from the rotor system if $v_\alpha < 0$. Drawing analogy with a single-degree-of-freedom mass point system, the above reasoning suggests that Equation (6.3) may be expressed as

$$W = |\underline{K} - \kappa \underline{I}| = [k_\alpha - m_\alpha v^2 + i(v_\alpha c_\alpha - v c)] H_\alpha(v, c) \quad (6.7)$$

m_α may be thought of as the modal mass, while c_α would be the modal damping coefficient. Extending the analogy one step further, the modal critical damping ratio may be defined as (6.1):

$$\beta_\alpha = \frac{c_\alpha}{2 m_\alpha v_\alpha} \quad (6.8)$$

Computation of (v_α, β_α) is of great importance since v_α indicates the frequency at which a natural mode tends to oscillate and $1/\beta_\alpha$ is an indication of the excitability (amplification factor) of the natural mode. The condition $\beta < 0$ signifies an unstable condition such that $\underline{x}_\alpha$ would require external dissipative restraint in order not to become unbounded in amplitude.

In the study of rotor dynamics, it is usually desirable to solve the eigenvalue problem within a specified range of v . Since the elements

of $\underline{K}$ are smooth functions of v , it is feasible to adopt an interpolation strategy. The isotropic rotor problem would be solved at suitable intervals of v through the desired range. Since the rank of $\underline{K}$ is reduced to a minimum by truncation, an accurate interpolation scheme can be systematically implemented very economically.

6.3 Computation of the Conservative System

Since the rotor structure as modelled in Sections 5.1 and 5.2 is non-dissipative, and if the actual bearing characteristics are also conservative, then one can expect c_α , $v_\alpha = 0$ so that Equation (6.7) becomes

$$W = (k_\alpha - m_\alpha v^2) H_\alpha(v)$$

In fact, if up to N natural modes are of interest, then one can write

$$W = \prod_{\alpha=1}^N (k_\alpha - m_\alpha v^2) H_N(v) \quad (6.9)$$

It is relatively straightforward to determine the roots of such an equation by numerical interpolation. However, for rotors of common interest and in engineering units, v would be a relatively large number, while m would be a number of moderate magnitude. Thus Equation (6.9) tends to behave like an undulating function which has an ever-increasing envelope. Numerical interpolation of such a function may not be accurate if it is to be performed over a wide range of v . It has been determined through fairly extensive testing that a cubic spline interpolation procedure is quite satisfactory, provided each element of K (therefore κ also) is first divided by v^2 and a uniform geometric progression is adopted with consecutive increments not to exceed 10 percent. The cubic spline interpolation algorithm is discussed in Appendix B.

6.4 Computation of the Non-Conservative System

If it is not known in advance that the rotor system is conservative,

v_α is an unknown quantity. The eigenvalue problem involves the solution of

$$\begin{aligned} W(v_\alpha, \kappa_\alpha = i v_\alpha) &= |\underline{K} - i v_\alpha c_\alpha \underline{I}| \\ &= U(v_\alpha, c_\alpha) + i V(v_\alpha, c_\alpha) \\ &= 0 \end{aligned} \quad (6.10)$$

(U, V) are required to vanish simultaneously, yielding two conditions to determine the values of (v_α, c_α) . This can be done using a two-parameter Newton iterative scheme. Assuming that (v'_α, c'_α) are fairly good estimates for (v_α, c_α) so that

$$\delta v = v_\alpha - v'_\alpha; \quad \delta c = c_\alpha - c'_\alpha \quad (6.11)$$

are respectively small quantities in comparison to (v_α, c_α) ; then one can approximate Equation (6.10) by its Taylor series expansion:

$$\begin{aligned} 0 &= U' + \delta v \frac{\partial U'}{\partial v'_\alpha} + \delta c \frac{\partial U'}{\partial c'_\alpha} + \dots \\ 0 &= V' + \delta v \frac{\partial V'}{\partial v'_\alpha} + \delta c \frac{\partial V'}{\partial c'_\alpha} + \dots \end{aligned} \quad (6.12)$$

The necessary improvements are found by truncating Equation (6.12) beyond the first order expansions and making use of the Kramer's rule:

$$\begin{bmatrix} \delta v \\ \delta c \end{bmatrix} = \left\{ \frac{\partial U'}{\partial v'_\alpha} \frac{\partial V'}{\partial c'_\alpha} - \frac{\partial U'}{\partial c'_\alpha} \frac{\partial V'}{\partial v'_\alpha} \right\}^{-1} \begin{bmatrix} V' \frac{\partial U'}{\partial c'_\alpha} - U' \frac{\partial V'}{\partial c'_\alpha} \\ U' \frac{\partial V'}{\partial v'_\alpha} - V' \frac{\partial U'}{\partial v'_\alpha} \end{bmatrix} \quad (6.13)$$

where

(U', V') are values of (U, V) at (v'_α, c'_α) .

In principle, the above formulae can be used repeatedly until $(\delta v, \delta c)$ become negligibly small. In practice, a number of algorithmic difficulties must be resolved. They are enumerated as follows:

- A logical procedure is needed to initiate the iteration process; what should the first values of (v'_α, c'_α) be?
- If (v'_α, c'_α) are not sufficiently close to (v_α, c_α) , an excessively large value of δv would be found so that the improved value $(v'_\alpha + \delta v)$ would be outside the frequency range for which $\underline{K}$ is available; how should the iteration process continue?
- Suppose one set of (v_α, c_α) has been established, how can one avoid repeated convergence to the same set in subsequent iterations?
- Since v_α and c_α have different units, how should c_α be scaled?

First Estimates for (v'_α, c'_α)

There is no simple way to estimate c'_α for the first time. In fact, one does not even know whether or not the system is conservative. Under the circumstances, $c'_\alpha = 0$ may be assumed for the first time. This has been found satisfactory even for cases where the final c_α ultimately approaches a relatively large magnitude. With such an assumed c'_α , one wishes to determine v'_α such that (U', v') are both as close to null values as possible. This is equivalent to seeking the minimum condition of $U'^2 + v'^2$; or

$$U' \frac{\partial U'}{\partial v'_\alpha} + v' \frac{\partial v'}{\partial v'_\alpha} = 0; \quad \left(\frac{\partial U'}{\partial v'_\alpha}\right)^2 + \left(\frac{\partial v'}{\partial v'_\alpha}\right)^2 + U' \frac{\partial^2 U'}{\partial v'^2_\alpha} + v' \frac{\partial^2 v'}{\partial v'^2_\alpha} > 0 \quad (6.14)$$

within the assigned frequency range. This can be readily accomplished with the cubic spline interpolation method which is described in Appendix B.

It is quite possible that $U'^2 + v'^2$ does not have a minimum in the

specified range of v , then the geometrical mean of the extreme limits can be used as the first guess for v'_α .

A provision is made to allow the user to enter first estimates for (v'_α, c'_α) of his choice. This is done by assigning the value -1 to the parameter IBEG in input card 14 and then using input card 17 to enter the desired first estimates.

Excessive δv

If the current values of (v'_α, c'_α) are not sufficiently close to the eigenvalue set, δv would be excessively large in magnitude to project the improved v'_α beyond either extreme of the specified frequency range. Since an extrapolation scheme would not be dependable, it is necessary to keep trial values of v'_α within the limits at all times. Thus, upon detecting the trend for v'_α to pass beyond either limit while the current v'_α is not at the same limit, δv is scaled down to place v'_α at the limit while δc is scaled down by the same proportion. If the current v'_α is already at the same limit, then the geometrical mean of the extreme limits of v would be used as the next trial value of v'_α while c'_α would not be changed.

If the specified range of v actually does not contain an eigenvalue set, the above situation would be cycled indefinitely. A limit on the maximum number of iterations is imposed to terminate the search. Experience has indicated that a maximum limit of 20 iteration steps for each set of (v_α, c_α) is satisfactory. In most test cases, convergence is reached in about six iterations; only very seldom it was found necessary to exceed 10 steps.

If the iteration progression should attempt to exceed either limit of the frequency range repeatedly, the value of the iteration residue $(u')^2 + (v')^2$ would accordingly oscillate. Such oscillations are allowed to occur three times. When the fourth time is detected, the computation will be terminated and a message is printed out to indicate

the direction of shifting the frequency range for a subsequent trial, if so desired, as suggested by the iteration history.

Computation of (m_α, β_α)

Upon satisfying Equation (6.10) by repeated iterations with the aid of Equation (6.13), (v_α, c_α) become known. Since the iterative steps also involves the computations of

$$\left. \frac{\partial W}{\partial v} \right|_{v_\alpha, c_\alpha} = \left. \frac{\partial U}{\partial v} \right|_{v_\alpha, c_\alpha} + i \left. \frac{\partial V}{\partial v} \right|_{v_\alpha, c_\alpha}$$

and

$$\left. \frac{\partial W}{\partial c} \right|_{v_\alpha, c_\alpha} = \left. \frac{\partial U}{\partial c} \right|_{v_\alpha, c_\alpha} + i \left. \frac{\partial V}{\partial c} \right|_{v_\alpha, c_\alpha}$$

one can subsequently compute (m_α, β_α) .

If one formally differentiates Equation (6.7) with respect to v and c , it is found

$$\frac{\partial W}{\partial v} = (-2m_\alpha v - ic) H_\alpha + \{(k_\alpha - m_\alpha v^2) + i(v_\alpha c_\alpha - vc)\} \frac{\partial H_\alpha}{\partial v}$$

$$\frac{\partial W}{\partial c} = -iv H_\alpha + \{(k_\alpha - m_\alpha v^2) + i(v_\alpha c_\alpha - vc)\} \frac{\partial H_\alpha}{\partial c}$$

Allowing the limiting process $(v \rightarrow v_\alpha, c \rightarrow c_\alpha)$

$$\left. \frac{\partial W}{\partial v} \right|_{v_\alpha, c_\alpha} = (-2m_\alpha v_\alpha - ic_\alpha) H_\alpha(v_\alpha, c_\alpha)$$

$$\left. \frac{\partial W}{\partial c} \right|_{v_\alpha, c_\alpha} = -iv_\alpha H_\alpha(v_\alpha, c_\alpha)$$

H_α can be eliminated, yielding

$$\left. \frac{(\partial W / \partial v)}{(\partial W / \partial c)} \right|_{v_\alpha, c_\alpha} = \frac{c_\alpha}{v_\alpha} - i(2m_\alpha) \quad (6.15)$$

Therefore

$$m_\alpha = -\frac{1}{2} \operatorname{Im} \left\{ \frac{(\partial W / \partial v)}{(\partial W / \partial c)} \right\} \Big|_{v_\alpha, c_\alpha} \quad (6.16)$$

and

$$\beta_\alpha = \frac{\operatorname{Re} \left\{ \frac{(\partial W / \partial v)}{(\partial W / \partial c)} \right\}}{\operatorname{Im} \left\{ \frac{(\partial W / \partial v)}{(\partial W / \partial c)} \right\}} \Big|_{v_\alpha, c_\alpha} \quad (6.17)$$

The real part of Equation (6.15) yields the redundant condition

$$c_\alpha = v_\alpha \operatorname{Re} \left\{ \frac{(\partial W / \partial v)}{(\partial W / \partial c)} \right\} \Big|_{v_\alpha, c_\alpha}$$

since c_α is directly calculated in the iterative process. Accordingly,

$$\varepsilon_\alpha = \frac{c_\alpha - v_\alpha \operatorname{Re} \left\{ \frac{(\partial W / \partial v)}{(\partial W / \partial c)} \right\} \Big|_{v_\alpha, c_\alpha}}{v_\alpha \operatorname{Im} \left\{ \frac{(\partial W / \partial v)}{(\partial W / \partial c)} \right\} \Big|_{v_\alpha, c_\alpha}} \quad (6.18)$$

is an indicator of the precision of the numerical computation of the complex derivatives $(\partial W / \partial v, \partial W / \partial c)$.

Avoidance of Previously Determined (v_α, c_α)

Equation (6.7) can be extended to include all eigenvalue sets within the frequency range. Suppose N eigenvalue sets are in the range, then one can write

$$W = \prod_{\alpha=1}^N \{ (k_{\alpha} - m_{\alpha} v^2) + i(v_{\alpha} c_{\alpha} - vc) \} H_N(v, c) \quad (6.19)$$

H_N does not vanish in the range for any value of α . Upon finding the first set (k_1, m_1, c_1) , one can divide out the factor

$$(k_1 - m_1 v^2) + i(v_1 c_1 - vc)$$

to obtain

$$\begin{aligned} W_1 &= \frac{W}{(k_1 - m_1 v^2) + i(v_1 c_1 - vc)} \\ &= \prod_{\alpha=2}^N \{ (k_{\alpha} - m_{\alpha} v^2) + i(v_{\alpha} c_{\alpha} - vc) \} H_N(v, c) \end{aligned} \quad (6.20)$$

(U_1, V_1) and their derivatives are used in subsequent search for (v_2, c_2) . The process is repeated every time when a new set of (v_{α}, c_{α}) is found.

Scaling of c_{α}

The question of scaling c_{α} comes up when one introduces the concept of modal critical damping ratio, Equation (6-8), in which the modal mass m appears. Actually, without an appropriate scale for c_{α} , $(\partial U'/\partial c'_{\alpha}, \partial V'/\partial c'_{\alpha})$ which are needed during the iterative search for c_{α} , cannot be computed by finite difference.

Fortunately, these derivatives can be calculated by an analytical method. This derivation is as follows:

$$\frac{\partial W}{\partial c} = \sum_{m=1}^M \left[-i \frac{\partial W}{\partial (K_{mm} - i v c)} \right]$$

where M is the rank of the system and where $K_{mm} - i v c$ is the m th diagonal element of the matrix $[K - i v c I]$. The derivative $\frac{\partial W}{\partial (K_{mm} - i v c)}$ can be computed by using

two matrices. The first matrix, $\underline{K}_{(1)m}$, is that formed by substituting unity for the m th diagonal element in $[\underline{K} - i\nu c \underline{I}]$. The second matrix, $\underline{K}_{(0)m}$, is that formed by substituting zero for the m th diagonal element in $[\underline{K} - i\nu c \underline{I}]$. From these

$$\frac{\partial W}{\partial (K_{mm} - i\nu c)} = |\underline{K}_{(1)m}| - |\underline{K}_{(0)m}|$$

so that

$$\frac{\partial W}{\partial c} = -i\nu \sum_{m=1}^M \{ |\underline{K}_{(1)m}| - |\underline{K}_{(0)m}| \}$$

(6 21)

APPENDIX A

GYROSCOPIC INERTIA FOR SMALL LATERAL ANGULAR OSCILLATIONS

In the analysis of lateral vibrations of a high speed rotor, gyroscopic inertia must be considered if the motion involves an inclination of the rotor axis. The problem is essentially a straightforward application of Euler's theorem of angular momentum. However in the conventional presentation of Euler's theorem, the Euler angles are so chosen that a quadratic combination of their time derivatives appear in the angular inertia. Since the lateral inclinations are always small in practical problems, it is convenient to identify two of the Euler angles with them and hence the angular inertia can be linearly related to the time derivatives of the lateral inclinations.

The treatment to be presented applies either to a portion of a rotor, which can be regarded as a rigid body (see Section 5.2.1), or to an infinitesimal element of a flexible shaft segment, which is regarded as a rigid disk (see Section 5.2.2).

The angular momentum of a rigid body is

$$\vec{H} = \vec{\omega} \cdot I \quad (A-1)$$

$\vec{\omega}$ is the angular velocity; I is the second order moment of inertia tensor and is an invariant in body-fixed coordinates. Let $(\vec{i}_1, \vec{i}_2, \vec{i}_3)$ be a triad of unit Cartesian base vectors attached to the rigid body at its mass center, then

$$I = \vec{i}_k (I_{mm} \delta_{kl} - I_{kl}) \vec{i}_l \quad (A-2)$$

where I_{kl} is an element of the matrix

$$I = \int \begin{bmatrix} \xi^2 & \xi\eta & \xi\zeta \\ \eta\xi & \eta^2 & \eta\zeta \\ \zeta\xi & \zeta\eta & \zeta^2 \end{bmatrix} dM \quad (A-3)$$

dM is a mass element of the rigid body. (ξ, η, ζ) are coordinates of the location of dM with respect to the body fixed base vectors. δ_{kl} is the Kronecker delta. The summation convention applies in Equation (A-2). Since the origin coincides with the mass center, all off-diagonal terms of Equation (A-3) vanish. Thus,

$$I = \vec{i}_1' \vec{i}_1' I_1 + \vec{i}_2' \vec{i}_2' I_2 + \vec{i}_3' \vec{i}_3' I_3 \quad (A-4)$$

where,

$$\begin{aligned} I_1 &= \int (\eta^2 + \zeta^2) dM \\ I_2 &= \int (\zeta^2 + \xi^2) dM \\ I_3 &= \int (\xi^2 + \eta^2) dM \end{aligned} \quad (A-5)$$

(I_1, I_2) are the two transverse moments of inertia, I_3 is the polar moment of inertia.

The body fixed base vectors $(\vec{i}_1', \vec{i}_2', \vec{i}_3')$ may be related to a set of ground fixed base vectors $(\vec{i}_1, \vec{i}_2, \vec{i}_3)$. Let $\vec{i}_3'$ be coincident with the rotor axis and $\vec{i}_3$ be coincident with the bearing axis. $(\vec{i}_1', \vec{i}_2', \vec{i}_3')$ can be mapped onto $(\vec{i}_1'', \vec{i}_2'', \vec{i}_3'')$ through three successive rotations through the Euler angles (θ, ϕ, ψ) as illustrated in Figure 3.

If a rotation about $\vec{i}_1'$ through an angle θ is performed so that $\vec{i}_3'$ is made to fall on $\vec{i}_3''$. $\vec{i}_2'$ is accordingly moved to $\vec{i}_2''$. In matrix notation, this is represented by

$$\begin{bmatrix} \vec{i}_1' \\ \vec{i}_2' \\ \vec{i}_3' \end{bmatrix} = \theta \cdot \begin{bmatrix} \vec{i}_1'' \\ \vec{i}_2'' \\ \vec{i}_3'' \end{bmatrix}; \quad \theta = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\theta & \sin\theta \\ 0 & -\sin\theta & \cos\theta \end{bmatrix} \quad (A-6)$$

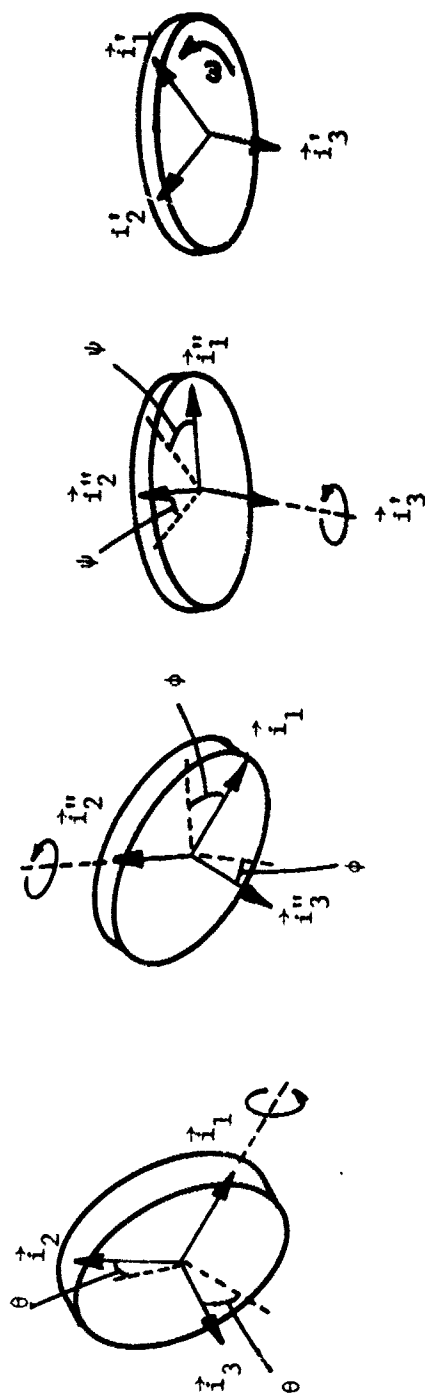


Figure 3 Transformation of Base Vectors

The second rotation is about $\vec{i}_2''$ through the angle ϕ

$$\begin{bmatrix} \vec{i}_1'' \\ \vec{i}_2'' \\ \vec{i}_3'' \end{bmatrix} = \underline{\underline{\phi}} \cdot \begin{bmatrix} \vec{i}_1' \\ \vec{i}_2' \\ \vec{i}_3' \end{bmatrix} ; \quad \underline{\underline{\phi}} = \begin{bmatrix} \cos \phi & 0 & -\sin \phi \\ 0 & 1 & 0 \\ \sin \phi & 0 & \cos \phi \end{bmatrix} \quad (\text{A-7})$$

Finally, rotating about $\vec{i}_3'$ through ψ :

$$\begin{bmatrix} \vec{i}_1' \\ \vec{i}_2' \\ \vec{i}_3' \end{bmatrix} = \underline{\underline{\psi}} \cdot \begin{bmatrix} \vec{i}_1'' \\ \vec{i}_2'' \\ \vec{i}_3'' \end{bmatrix} ; \quad \underline{\underline{\psi}} = \begin{bmatrix} \cos \psi & \sin \psi & 0 \\ -\sin \psi & \cos \psi & 0 \\ 0 & 0 & 1 \end{bmatrix} \quad (\text{A-8})$$

Note the (θ, ϕ) are actually the lateral inclinations and would be regarded as infinitesimal.

Time-derivatives of the Euler angles contribute to the angular velocity of the rigid body. Writing

$$\vec{\omega} = \vec{i}_1' \omega_1' + \vec{i}_2' \omega_2' + \vec{i}_3' \omega_3' \quad (\text{A-9})$$

then

$$\begin{aligned} \omega_1' &= \dot{\theta} \cos \phi \cos \psi + \dot{\phi} \sin \psi \\ \omega_2' &= \dot{\theta} \cos \phi \sin \psi + \dot{\phi} \cos \psi \\ \omega_3' &= \dot{\psi} + \dot{\theta} \sin \phi \end{aligned} \quad (\text{A-10})$$

Alternatively, the angular velocity may be written in terms of components with respect to the ground fixed base vectors:

$$\vec{\omega} = \vec{i}_1 \omega_1 + \vec{i}_2 \omega_2 + \vec{i}_3 \omega_3 \quad (\text{A-11})$$

$$\begin{aligned} \omega_1 &= \dot{\theta} + \dot{\psi} \sin\phi \\ \omega_2 &= \dot{\phi} \cos\theta - \dot{\psi} \cos\phi \sin\theta \\ \omega_3 &= \dot{\psi} \cos\phi \cos\theta + \dot{\phi} \sin\theta \end{aligned} \quad (\text{A-12})$$

Substituting Equations (A-4) and (A-9) into Equation (A-1), one obtains

$$\vec{H} = \vec{i}_1' \omega_1' I_1 + \vec{i}_2' \omega_2' I_2 + \vec{i}_3' \omega_3' I_3 \quad (\text{A-13})$$

Differentiating with time, it is found that the angular inertia is

$$\begin{aligned} \dot{\vec{H}} &= \vec{i}_1' \dot{\omega}_1' I_1 + \vec{i}_2' \dot{\omega}_2' I_2 + \vec{i}_3' \dot{\omega}_3' I_3 \\ &\quad + \omega_1' I_1 \dot{\vec{i}}_1' + \omega_2' I_2 \dot{\vec{i}}_2' + \omega_3' I_3 \dot{\vec{i}}_3' \end{aligned}$$

but since

$$\dot{\vec{i}}_1' = \vec{i}_2' \omega_3' - \vec{i}_3' \omega_2'; \quad \dot{\vec{i}}_2' = -\vec{i}_1' \omega_3' + \vec{i}_3' \omega_1'; \quad \dot{\vec{i}}_3' = \vec{i}_1' \omega_2' - \vec{i}_2' \omega_1'$$

therefore,

$$\begin{aligned} \dot{\vec{H}} &= \vec{i}_1' [\dot{\omega}_1' I_1 + \omega_2' \omega_3' (I_3 - I_2)] + \vec{i}_2' [\dot{\omega}_2' I_2 + \omega_3' \omega_1' (I_1 - I_3)] \\ &\quad + \vec{i}_3' [\dot{\omega}_3' I_3 + \omega_1' \omega_2' (I_2 - I_1)] \end{aligned} \quad (\text{A-14})$$

To obtain a ground fixed representation, the transformations given by Equations (A-6), (A-7), and (A-8) are applied in reverse:

$$\begin{aligned}
 \dot{\vec{H}} = & \vec{i}_1 \{ \cos\phi [\dot{H}_1'' + \omega_3' (\omega_2'' I_3 - H_2'')] + \sin\phi [\dot{H}_3'' - \omega_1' \omega_2' (I_1 - I_2)] \} \\
 & + \vec{i}_2 \{ \cos\theta [\dot{H}_2'' + \omega_3' (H_1'' - \omega_1'' I_3)] + \sin\theta \sin\phi [\dot{H}_1'' + \omega_3' (\omega_2'' I_3 - H_2'')] \\
 & \quad - \sin\theta \cos\phi [\dot{H}_3'' - \omega_1' \omega_2' (I_1 - I_2)] \} \\
 & + \vec{i}_3 \{ \cos\theta \cos\phi [\dot{H}_3'' - \omega_1' \omega_2' (I_1 - I_2)] - \cos\theta \sin\phi [\dot{H}_1'' + \omega_3' (\omega_2'' I_3 - H_2'')] \\
 & \quad + \sin\theta [\dot{H}_2'' + \omega_3' (H_1'' - \omega_1'' I_3)] \} \quad (A-15)
 \end{aligned}$$

$$\omega_1'' = \omega_1' \cos\psi - \omega_2' \sin\psi; \quad \omega_2'' = \omega_1' \sin\psi + \omega_2' \cos\psi;$$

$$H_1'' = \omega_1' \cos\psi I_1 - \omega_2' \sin\psi I_2; \quad H_2'' = \omega_1' \sin\psi I_1 + \omega_2' \cos\psi I_2;$$

$$\dot{H}_1'' = \dot{\omega}_1' \cos\psi I_1 - \dot{\omega}_2' \sin\psi I_2; \quad \dot{H}_2'' = \dot{\omega}_1' \sin\psi I_1 + \dot{\omega}_2' \cos\psi I_2;$$

$$\dot{H}_3'' = \dot{\omega}_3' I_3$$

(A-16)

Making use of Equation (A-10), various groups in the above relations are found to be

$$\dot{H}_1'' + \omega_3' (\omega_2'' I_3 - H_2'') =$$

$$I_0 \frac{d}{dt} (\cos\phi \dot{\theta}) + \Delta I \frac{d}{dt} (\cos\phi \cos 2\psi \dot{\theta} + \sin 2\psi \dot{\phi}) + I_3 \ddot{\phi} (\psi + \sin\phi \dot{\theta})$$

$$- I_0 \sin\phi \ddot{\phi} - \Delta I (\sin\phi \cos\phi \sin 2\psi \dot{\theta}^2 - \sin\phi \cos 2\psi \dot{\theta} \ddot{\phi})$$

$$\begin{aligned}
& \ddot{H}_2'' + \omega_3'(H_1'' - \omega_1'' I_3) \\
& = I_0 \ddot{\phi} + \Delta I \frac{d}{dt} (\cos \phi \sin 2\psi \dot{\theta} - \cos 2\psi \dot{\phi}) - I_3 \cos \phi (\dot{\psi} + \sin \phi \dot{\theta}) \dot{\theta} \\
& \quad + I_0 \sin \phi \cos \phi \dot{\theta}^2 + \Delta I \sin \phi (\cos \phi \cos 2\psi \dot{\theta} + \sin 2\psi \dot{\phi}) \dot{\theta} \\
& \ddot{H}_3'' - \omega_1' \omega_2' (I_1 - I_2) \\
& = I_3 \frac{d}{dt} (\dot{\psi} + \sin \phi \dot{\theta}) + \Delta I \{ \sin 2\psi [(\cos \phi \dot{\theta})^2 - \dot{\phi}^2] - 2 \cos 2\psi (\cos \phi \dot{\theta}) \dot{\phi} \}
\end{aligned} \tag{A-17}$$

where $I_0 = \frac{1}{2}(I_1 + I_2)$ is the mean transverse inertia and $\Delta I = \frac{1}{2}(I_1 - I_2)$ is the transverse inertia differential. Consolidating these expressions, one finds

$$\begin{aligned}
\dot{H} = & \vec{i}_1 \left[I_0 \frac{d}{dt} (\cos^2 \phi \dot{\theta}) + \Delta I \frac{d}{dt} \left\{ \cos \phi \left[\cos 2\psi (\cos \phi \dot{\theta}) + \sin 2\psi \dot{\phi} \right] \right. \right. \\
& \quad \left. \left. + I_3 \frac{d}{dt} \left[\sin \phi (\dot{\psi} + \sin \phi \dot{\theta}) \right] \right\} \right] \\
& + \vec{i}_2 \left[I_0 \frac{d}{dt} \left\{ \cos \theta \dot{\phi} + \sin \theta \sin \phi (\cos \phi \dot{\theta}) \right\} \right. \\
& \quad + \Delta I \frac{d}{dt} \left\{ \sin \theta \sin \phi \left[\cos 2\psi (\cos \phi \dot{\theta}) + \sin 2\psi \dot{\phi} \right] \right. \\
& \quad \left. + \cos \theta \left[\sin 2\psi (\cos \phi \dot{\theta}) - 2\psi \dot{\phi} \right] \right\} \\
& \quad \left. - I_3 \frac{d}{dt} \left[\sin \theta \cos \phi (\dot{\psi} + \sin \phi \dot{\theta}) \right] \right] \\
& \quad + \vec{i}_3 \left[I_3 \frac{d}{dt} \left[\cos \theta \cos \phi (\dot{\psi} + \sin \phi \dot{\theta}) \right] \right. \\
& \quad \left. - I_0 \frac{d}{dt} \left[\cos \theta \sin \phi (\cos \phi \dot{\theta}) - \sin \theta \dot{\phi} \right] \right. \\
& \quad \left. + \Delta I \frac{d}{dt} \left\{ \sin \theta \left[\sin 2\psi (\cos \phi \dot{\theta}) - \cos 2\psi \dot{\phi} \right] \right. \right. \\
& \quad \left. \left. - \cos \theta \sin \phi \left[\cos 2\psi (\cos \phi \dot{\theta}) + \sin 2\psi \dot{\phi} \right] \right\} \right]
\end{aligned} \tag{A-18}$$

For a small deflection analysis, $(\theta, \phi, \psi - \omega t)$ may be regarded to be infinitesimal, ω being the shaft rotation speed; then one obtains

$$\begin{aligned} \ddot{\mathbf{h}} \approx & \mathbf{i}_1 \left\{ I_0 \frac{d^2 \theta}{dt^2} + \Delta I \frac{d}{dt} (\cos 2\omega t \frac{d\theta}{dt} + \sin 2\omega t \frac{d\phi}{dt}) + \omega I_3 \frac{d\phi}{dt} \right\} \\ & + \mathbf{i}_2 \left\{ -\Delta I \frac{d}{dt} (\cos 2\omega t \frac{d\theta}{dt}) - \omega I_3 \frac{d\theta}{dt} + I_0 \frac{d^2 \phi}{dt^2} + \Delta I \frac{d}{dt} (\sin 2\omega t \frac{d\phi}{dt}) \right\} \\ & + \mathbf{i}_3 \left\{ I_3 \frac{d^2 \delta\psi}{dt^2} \right\} \end{aligned}$$

where $\delta\psi = \psi - \omega t$ is the infinitesimal torsional angular displacement.

APPENDIX B

CUBIC SPLINE INTERPOLATION

B.1 Interpolation Requirements

Use of polynomials to perform curve fitting or interpolation is a common practice in engineering work. In each of the five major modes of analysis of flexible rotor dynamics, namely:

- o critical speeds,
- o damped unbalance response,
- o asynchronous resonance,
- c damped asynchronous response, and
- o stability analysis,

an accurate interpolation on the determinant of the system impedance matrix and/or its derivatives is performed.

When seeking critical speeds, rotor spin rate and vibration frequency are equal. The system is conservative and isotropic. Only the forward whirl motion is of interest. The determinant of the impedance matrix is real and presumably a smooth function of frequency. Critical speeds are the roots of the real determinant. This calls for a root searching algorithm. An asynchronous resonance analysis seeks all the natural frequencies within a frequency range of interest at a fixed rotor speed. The impedance matrix, again, has a real and presumably a smoothly varying determinant. Similarly as in the critical speed analysis, a root searching algorithm is needed.

When performing an unbalance response calculation, the frequencies of interest can be specifically specified. However, the most interesting may not be known beforehand. Therefore it is useful to locate first the "damped" critical speeds, then perform corresponding response calculations. A similar situation exists when the damped asynchronous response problem is solved. The "damped" resonance problem, either synchronous or asynchronous, requires an algorithm for the complex eigenvalue problem

discussed in Appendix A. The explicit parameter is directly related to the system damping. An implicit parameter is the "damped" natural frequency. A pair of these parameters is determined for every natural mode by requiring both the real and the imaginary parts of the complex determinant of the characteristic matrix to vanish. The complex eigenvalue problem is also involved in the stability analysis. In the latter case, a negative sign for the system damping indicates an unstable mode. The system damping can further be expressed in terms of a critical damping ratio. A numerically small, albeit positive, critical damping ratio indicates a high "Q" or sensitive natural mode. In each of these three modes of analysis, solution of the complex eigenvalue problem is a central issue. The procedure for solving the complex eigenvalue problem, in turn, requires repeated use of an efficient numerical interpolation scheme.

To understand the requirements of a numerical interpolation scheme to be used in the complex eigenvalue algorithm, it is useful to outline briefly the major computation steps. The method of computation is iterative in character. It is necessary to begin with an initial guess for the two parameters, system damping coefficient and natural frequency. The system damping coefficient is initially assumed to be zero, but one is still left with the question of finding the best starting frequency. Since both real and imaginary parts of the characteristic determinant should vanish upon convergence to a solution, a positive minimal of the square of its magnitude should represent a suitable criterion for the starting frequency. Two specific computations are required:

- o Since a minimum must have a vanishing first derivative, locate roots of the first derivative.
- o Select that minimum which has a positive second derivative.

Upon establishing a starting condition, it is necessary to determine the "present error" and the best "corrections" to the two parameters in order to continue the iterative process. These require interpolation of the complex determinant and its derivatives at the current value of frequency.

B.2 Description of the Spline Curve-fitting Concept

The spline interpolation allows one to curve fit a set of data points precisely and to maintain a certain degree of smoothness. This method utilizes an odd order $(2n+1)$ polynomial $(n \geq 1)$ segmentally in consecutive intervals, maintaining continuity up to the $2n$ -th derivative at all internal points while permitting n constraints at each end. It turned out that the cubic spline $(n=1)$ would be the simplest form to satisfy various requirements indicated previously.

Within each interval, a cubic polynomial allows the presence of up to two extrema, of which only one may be a minimum. The locations of these extrema are explicitly given by the quadratic formula. The determination of roots is somewhat tedious. The procedures for these calculations will be given later following a description for the determination of the polynomial coefficients in each interval. A common choice of the constraint at either end is a vanishing second derivative.

B.3 The Cubic Spline

Suppose N data points, $y_n = y(x_n)$ for $n = 1$ through N , are known. The $N-1$ intervals, $\Delta x_n = x_{n+1} - x_n$ for $n = 1$ through $N-1$, do not have to be uniform. A cubic polynomial applicable in the interval $x_n \leq x \leq x_{n+1}$ is

$$y = \left(\frac{x-x_n}{\Delta x_n}\right)y_{n+1} + \left(\frac{x_{n+1}-x}{\Delta x_n}\right) \left\{ y_n + (x-x_n) \left[1 + \frac{x-x_n}{\Delta x_n} \right] \left(\theta_n - \frac{\Delta y_n}{\Delta x_n} \right) + \left(\frac{x-x_n}{2} \right)^2 K_n \right\} \quad (B-1)$$

where, (θ_n, K_n) are respectively first and second derivatives of y at x_n while $\Delta y_n = y_{n+1} - y_n$. Differentiating three times successively,

$$y' = \frac{\Delta y_n}{\Delta x_n} - \frac{(x-x_n)}{\Delta x_n} \left[1 + \frac{(x-x_n)}{\Delta x_n} \right] \left(\theta_n - \frac{\Delta y_n}{\Delta x_n} \right) - \frac{(x-x_n)^2}{2\Delta x_n} K_n \\ + \left(\frac{x_{n+1}-x}{\Delta x_n} \right) \left\{ \left[1 + \frac{2(x-x_n)}{\Delta x_n} \right] \left(\theta_n - \frac{\Delta y_n}{\Delta x_n} \right) + (x-x_n) K_n \right\} \quad (B-2)$$

$$y'' = \frac{2}{\Delta x_n} \left[1 + \frac{2(x-x_n)}{\Delta x_n} \right] \left(\theta_n - \frac{\Delta y_n}{\Delta x_n} \right) - \frac{2(x-x_n)}{\Delta x_n} K_n \\ + \frac{(x_{n+1}-x)}{\Delta x_n} \left\{ \frac{2}{\Delta x_n} \left(\theta_n - \frac{\Delta y_n}{\Delta x_n} \right) + K_n \right\} \quad (B-3)$$

$$y''' = -\frac{3}{\Delta x_n} \left\{ \frac{2}{\Delta x_n} \left(\theta_n - \frac{\Delta y_n}{\Delta x_n} \right) + K_n \right\} = \text{const} \quad (B-4)$$

Substituting $x = x_{n+1}$ into above, since continuity up to the second derivative is maintained

$$\theta_{n+1} = y'_{n+1} = 3 \left(\frac{\Delta y_n}{\Delta x_n} \right) - 2 \theta_n - \frac{\Delta x_n}{2} K_n \quad (B-5)$$

$$K_{n+1} = y''_{n+1} = \frac{6}{\Delta x_n} \left(\frac{\Delta y_n - \theta_n}{\Delta x_n} \right) - 2 K_n \quad (B-6)$$

A recurrence relationship can be developed by writing

$$K_n = a_n \theta_n + b_n; \quad K_{n+1} = a_{n+1} \theta_{n+1} + b_{n+1} \quad (B-7)$$

Eliminating (θ_n, K_n) among above relationships, one obtains

$$K_{n+1} = \left(2 + \frac{\Delta x_n}{2} a_n \right)^{-1} \left\{ \frac{2}{\Delta x_n} (3 + \Delta x_n a_n) \theta_{n+1} - \frac{3}{\Delta x_n} (2 + \Delta x_n a_n) \frac{\Delta y_n}{\Delta x_n} \right. \\ \left. - b_n \right\} \quad (B-8)$$

Comparing with Equation (B-7), with n replaced by $n+1$, one finds

$$a_{n+1} = \frac{2(3+\Delta x_n a_n)}{\Delta x_n (2+\Delta x_n a_n)}$$

$$b_{n+1} = \frac{\left\{ b_n + \frac{3}{\Delta x_n} (2+\Delta x_n a_n) \frac{\Delta y_n}{\Delta x_n} \right\}}{(2+\Delta x_n a_n)} \quad (B-9)$$

These are the recurrence formulae for (a_n, b_n) . Starting with the condition $K_1 = 0$ such that $a_1 = b_1 = 0$, Equations (B-9) can be applied repeatedly to generate the entire set of (a_n, b_n) for $n = 2$ through N . Now, substituting $K_n = a_n \theta_n + b_n$ into Equation (B-6) and solving for θ_n :

$$\theta_n = \frac{3 \frac{y_n}{x_n} - x_n b_n - \frac{x_n}{2} K_{n+1}}{(3 + \Delta x_n a_n)} \quad (B-10)$$

For $n = N$, since $K_{N+1} = 0$, therefore

$$\theta_N = \frac{3 \frac{\Delta y_N}{\Delta x_N} - \Delta x_N b_N}{3 + \Delta x_N a_N} \quad (B-11)$$

where upon, Equation (B-7) can be used to calculate K_N , and the process can be repeated to obtain (θ_n, K_n) for successively smaller n .

To summarize, the cubic-spline curve-fitting procedure includes the following:

1. Set $(n = 1; a_n = b_n = 0)$
2. Use Equations (B-9) to obtain (a_{n+1}, b_{n+1}) repeatedly until (a_n, b_n) are determined for the entire set $n = 1$ through N .
3. Set $(n = N, K_{n+1} = 0)$
4. Use Equation (B-10) to obtain θ_n . If current n is 1, the curve-fitting procedure has completed; otherwise continue.

5. Calculate K_n using Equation (B-7).

6. Decrease n by 1; go back to Step 4.

The above procedure can be used for any $n \geq 2$.

Upon completing the curve-fitting calculations, (θ_n, K_n) are known for every interval of $n = 1$ through N . Within the interval, the interpolation formula and its derivatives are

$$\begin{aligned}
 y &= y_n + \theta_n(x-x_n) + \frac{K_n}{2}(x-x_n)^2 \\
 &\quad - \frac{1}{\Delta x_n} \left[\frac{1}{2} K_n + \frac{1}{\Delta x_n} \left(\theta_n - \frac{\Delta y_n}{\Delta x_n} \right) \right] (x-x_n)^3 \\
 y' &= \theta_n + K_n(x-x_n) - \frac{3}{\Delta x_n} \left[\frac{1}{2} K_n + \frac{1}{\Delta x_n} \left(\theta_n - \frac{\Delta y_n}{\Delta x_n} \right) \right] (x-x_n)^2 \\
 y'' &= K_n - \frac{3}{\Delta x_n} \left[K_n + \frac{2}{\Delta x_n} \left(\theta_n - \frac{\Delta y_n}{\Delta x_n} \right) \right] (x-x_n)
 \end{aligned} \tag{B-12}$$

B.4 Determination of Stationary Values

The stationary values are found by solving for

$$y' = 0$$

or

$$\frac{x(\alpha) - x_n}{\Delta x_n} = \frac{K_n \pm \sqrt{K_n^2 + \frac{6\theta_n}{\Delta x_n} \left[K_n + \frac{2}{\Delta x_n} \left(\theta_n - \frac{\Delta y_n}{\Delta x_n} \right) \right]}}{\left[K_n + \frac{2}{\Delta x_n} \left(\theta_n - \frac{\Delta y_n}{\Delta x_n} \right) \right]} \tag{B-13}$$

for $\alpha = 1, 2$

For an extreme value to be within the interval, the following constraint must be satisfied

$$0 \leq \frac{x_{(\alpha)} - x_n}{\Delta x_n} < 1 \quad (\text{B-14})$$

The righthand bound is left open because x_{n+1} may be regarded to belong to the next interval (except when $n = N$). α is a positive integer not greater than 2. The following convention is adopted:

$$x_n \leq x_{(1)} \leq x_{(2)} < x_{n+1} \quad (\text{B-15})$$

Upon finding an extreme value, $y''_{(\alpha)} = y''(x = x_{(\alpha)})$ is calculated. $x_{(\alpha)}$ is

$$\left. \begin{array}{l} \text{a maximum} \\ \text{a minimum} \\ \text{an inflexion} \end{array} \right\} , \text{ if } y''_{(\alpha)} \begin{array}{l} < \\ > \\ = \end{array} \left. \begin{array}{l} \\ \\ \end{array} \right\} 0 \quad (\text{B-16})$$

B.5 Roots of the Cubic Sp'line

The roots of the cubic spline are sought in each interval. Again x_{n+1} is regarded as an external point (except for $n = N$). In general, up to three roots are possible. The extreme values divide the interval to up to three sub-intervals. Each sub-interval, however, cannot contain more than one root. Thus it is expedient to first identify the sub-intervals and then to determine whether or not a root exists within each sub-interval.

If the spline cubic vanishes at the starting point of the sub-interval, there can be no other root in the same sub-interval, and root-testing can immediately proceed to the next sub-interval. In the following, it will be presumed that the starting point is not a root. The existence of a root within the sub-interval is indicated by a sign reversal of the end points. When this is ascertained, the polynomial is calculated at the midpoint of the sub-interval and its magnitude is checked against $|\Delta y_n|$ for convergence. If necessary, further narrowing down of the sub-interval is done by excluding the half which is bounded by polynomial values of the same sign. The process is continued until a convergence test is passed.

APPENDIX C

LISTING OF SOURCE PROGRAM

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(0001) C ROTOR SUBSTRUCTURE VIBRATION PROGRAM
(0002) C *RSVP* BASIC VERSION DECEMBER 31, 1974 CHTP
(0003) C SHAKER RESEARCH CORPORATION
(0004) C
(0005) C SUPPLEMENTARY OUTPUT IS WRITTEN INTO I/O DEVICE (10)
(0006) C
(0007) C VERSION 76.02 JUNE 7, 1976
(0008) C MODIFIED FOR WPAFB
(0009) C
(0010) C VERSION 78.05 MAY 18, 1978
(0011) C FULL CAPABILITY WITH STREAMLINED I/O
(0012) C
(0013) C VERSION 79.05 MAY 01, 1979
(0014) C UPDATED FOR UNION COLLEGE COURSE
(0015) C
(0016) C VERSION 79.06 MAY 22, 1979
(0017) C PARAMETER 'LIST' REMOVED FROM INPUT
(0018) C
(0019) C VERSION 79.07 SEPTEMBER 25, 1979
(0020) C DOUBLE PRECISION PEAL ALGEBRA VERSION
(0021) C
(0022) C VERSION 79.08 DECEMBER 6, 1979
(0023) C TESTED FOR SAMPLES INCLUDED IN AIR FORCE REPORT
(0024) C
(0025) C VERSION 79.09 DECEMBER 13, 1979
(0026) C DIMENSION ALLOWANCE INCREASED TO 75 SEGMENTS
(0027) C
(0028) C VERSION 79.10 DECEMBER 20, 1979
(0029) C DOUBLE PRECISION SPECIFICATIONS REMOVED
(0030) C
(0031) C *****
(0032) C
(0033) C
(0034) C FEATURES TO BE INCLUDED IN THE FUTURE:
(0035) C (1) ASSIGN THE LAST STATION WITH DEFAULT K8=8
(0036) C (2) AUTOMATIC RUNNING OF TORSIONAL VIBRATIONS
(0037) C E.G. IRUN=6 FOR TORSIONAL RESONANCE
(0038) C INTEGER TITLE(16), IDENT(4)
(0039) C COMMON/AMH/F, FF, XS(4,2), F1, FF1, SS
(0040) C COMMON/AVIB/AA5(80,8,4)
(0041) C COMMON/ATEST1/B1(75), B2(75), B3(75), B4(75), B5(75), B6(75)
(0042) C COMMON/ATEST2/UO(80,4)
(0043) C COMMON/ATEST3/VO(80,8), A5(80,8,4)
(0044) C COMMON/BSTEP/D5(4,2)
(0045) C COMMON/CSTAT/X(75), Z(76)
(0046) C COMMON/ACOU/S4(4), A6(4,6)
(0047) C COMMON/ABRG/S5(4,2), T5(4,2)
(0048) C COMMON/AHIN/C4(4), W4(4), P4(4), T4(4), Y4(4)
(0049) C COMMON/AEND/U(80,2), ZH(76), ZK(20), FFRT
(0050) C COMMON/BNODE/W(76), P(76), T(76), Y(76)
(0051) C COMMON/VNODE/PS(76)
(0052) C COMMON/VHIN/P4S(4)
(0053) C COMMON/AFREQ/FREQ(5,11), PCC, JFQ(5), IFRE
(0054) C COMMON/TORL/TORD(5,11)

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(0055) COMMON/IMIN/N1(5),N2(5)
(0056) COMMON/ANODE/N3(76)
(0057) COMMON/ABEND/LIP,L4P1,I8,I5
(0058) COMMON/AINI/N8(76),K8(76),J8
(0059) COMMON/CHAD1/TITLE,L1,L2,L3,L4,L5,LIST/KR/KW,KR
(0060) COMMON/ASTEP/J4,LB,M5,N5(4)
(0061) COMMON/AINER/TRAC(75)
(0062) COMMON/PRMS/IRUN,ITYPE,IBRG,IDIAG
(0063) DIMENSION N4(4),XSS(4,2,11),SOO(11)
(0064) DIMENSION X5(4,2),Y5(4,2),W5(4,2),O5(4,2),ZBRG(4)
(0065) DIMENSION C5(2,5),KTORS(20),KBEND(20),JBRG(4)
(0066) 9998 FORMAT (1H )
(0067) KR = 5
(0068) KW = 6
(0069) READ(KR,8000) NCASE,KRUN
(0070) IF(NCASE.EQ 0) GO TO 4321
(0071) READ (KR,1000) IDENT,TITLE
(0072) 1000 FORMAT (20A4)
(0073) READ(KR,8000) LSEG,LMAT,LMAS,LBEA,LTYP,LEXI,LPRI
(0074) I5=LTYP
(0075) J8=LEXI
(0076) L1=LSEG
(0077) L2=LMAT
(0078) L3=LMAS
(0079) L4=0
(0080) L5=LBEA
(0081) LIST = 1
(0082) IF (I5.EQ 1) LPRI =-1
(0083) 8000 FORMAT (16I5)
(0084) CALL HEAD1
(0085) GO TO 8
(0086) C
(0087) C INPUT ERROR MESSAGES
(0088) C
(0089) 2005 WRITE (KW,1005)
(0090) 1005 FORMAT (43H FIRST SEGMENT MUST BE ASSIGNED A MATERIAL /)
(0091) GOTO 9999
(0092) 1854 WRITE (KW,1007) N
(0093) 1007 FORMAT (21H THERE IS NO NODE NO.,I3/)
(0094) GOTO 9999
(0095) 12 WRITE (KW,1012)
(0096) 1012 FORMAT (31H THERE MUST BE MORE BEARING(S) /)
(0097) GOTO 9999
(0098) 14 WRITE (KW,1014)
(0099) 1014 FORMAT (35H COUPLING MUST BE AN INTERNAL NODE /)
(0100) GOTO 9999
(0101) 8 Z(1) = 0
(0102) WRITE (KW,8006)
(0103) 8006 FORMAT (/17H SHAFT DIMENSIONS/8H SEGMENT,T12,6HLENGTH,T24,
(0104) +4HI.D.,T35,4HO.D.,T45,6HM.I.D.,T56,6HM.O.D./6H NO.
(0105) +5(11H (IN) /1H )
(0106) C
(0107) C FOR L=1,L1
(0108) C

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(0109)      DO 9 L=1,L1
(0110)      READ(KR,8001) LO, NULL, X(L), D1, D2, D3, D4
(0111) 8001  FORMAT (2I5, 7F10.0)
(0112)      Z(L+1) = Z(L)+X(L)
(0113)  C    CALCULATE SEGMENT FUNCTIONS (B1(L), B2(L), B3(L), B4(L), B5(L))
(0114)      WRITE (KW, 8002) L, X(L), D1, D2, D3, D4
(0115) 8002  FORMAT (I5, T10, 5(F9.4, 2X), F9.4)
(0116)      P1 = D2*D2
(0117)      P2 = D1*D1
(0118)      P3 = P1+P2
(0119)      P7 = P1-P2
(0120)      P5 = D4*D4
(0121)      P6 = D3*D3
(0122)      BB=P5+P6
(0123)      P5 = P5-P6
(0124)      P6=BB*P5
(0125)      B1(L) = .7853981633975*P7
(0126)      B2(L) = B1(L)*P3/16
(0127)      B1(L) = .7853981633975*P5
(0128)      A1 = P3*P7
(0129)      TRA(L)=B1(L)/16.0*BB*X(L)
(0130)      B3(L) = P5/A1
(0131)      B4(L)=P6/A1
(0132)      B5(L)=0.0
(0133)  9    B6(L)=BB*B4(L)
(0134)      L1P = L1+1
(0135)      WRITE (KW, 8007)
(0136) 8007  FORMAT (16H1SHAFT MATERIALS//9H STARTING, T12, 7HDENSITY, T21,
(0137)      +21HYOUNG'S MOD SHEAR MOD/7H  MODE, T10.11H(LBS/CU-IN),
(0138)      +T24, 5H(PSI), T35, 5H(PSI)/1H )
(0139)      DO 21 L=1,2
(0140)      READ (KR, 8111) NMAT, N, DO, E, G
(0141) 8111  FORMAT(2I5, 3E10.4)
(0142)      WRITE (KW, 8020) N, DO, E, G
(0143) 8020  FORMAT (I5, 5X, F7.4, 3X, 1P2E11.4)
(0144)      IF (L.GT.1) GO TO 21
(0145)      B9 = DO/386.4
(0146)      C = B9/G
(0147)      BB9=B9
(0148)      B9 = B9/E
(0149)      D = DO
(0150)      E1 = E
(0151)      G1=G
(0152)      IF (N.NE.1) GO TO 2005
(0153)      IF (L2.GE.2) GO TO 21
(0154)      GOTO 22
(0155) 21    CONTINUE
(0156) 22    L = 2
(0157)      DO 25 K=1,L1
(0158)      IF (K.EQ.1.OR.K.NE.N) GO TO 24
(0159)      B9 = DO/386.4
(0160)      C = B9/G
(0161)      BB9=B9
(0162)      B9 = B9/E

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(0163)      D = D0
(0164)      E1 = E
(0165)      G1=G
(0166)      IF (L.EQ.L2) GO TO 24
(0167)      L = L+1
(0168)      READ (KR,8111) N,AT,N,D0,E,G
(0169)      WRITE (KW,8020) N,D0,E,G
(0170) 24    B1(K) = D*B1(K)
(0171)      B5(K)=2*G1*B2(K)
(0172)      B2(K) = E1*B2(K)
(0173)      TRA(K)=BB9*TRA(K)
(0174)      B6(K)=0.0625*B9*B6(K)
(0175)      B3(K) = 2.0*(B9*B3(K))*0.25
(0176) 25    B4(K) = SQRT(C*B4(K))
(0177)      IF (L3.GE.1) GO TO 30
(0178)      M3 = 0
(0179)      GOTO 31
(0180) 30    WRITE (KW,8008)
(0181) 8008  FORMAT (//16H LUMPED INERTIAS//7H  NODAL,T11,6HWEIGHT,T23,
(0182)      +5HPOLAR,T34,5HTRANS,T46,2HCG/8H STATION,
(0183)      +T22,7HINERTIA,T33,7HINERTIA,T44,7HOFF-SET,
(0184)      +/T12,4H(LB),T21,10H(LB-SQ IN),T32,10H(LB-SQ IN),T45,4H(IN))
(0185)      DO 26 L=1,L3
(0186)      READ(KR,8001) L0,N3(L),W(L),P(L),T(L),Y(L)
(0187)      N = N3(L)
(0188)      WRITE (KW,8002) N3(L),W(L),P(L),T(L),Y(L)
(0189)      IF (N.GT.L1+1) GO TO 1854
(0190) 26    CONTINUE
(0191)      M3 = "3(1)
(0192) 31    J3 = .
(0193)      WRITE (KW, 9998)
(0194)      IF (L4.EQ.0) GOTO 29
(0195)      DO 28 L=1,L4
(0196)      READ(KR,8001) L0,N4(L),S4(L),C4(L),W4(L),P4(L),T4(L),Y4(L)
(0197)      WRITE (KW,8002) N4(L),W4(L),P4(L),T4(L),Y4(L),C4(L),S4(L)
(0198)      N = N4(L)
(0199)      IF (N.EQ.1.OR.N.GT.L1) GOTO 14
(0200) 28    CONTINUE
(0201) 29    L4P1=L4+1
(0202) C
(0203) C      INTEGRATE STATIC WEIGHT EFFECTS
(0204) C
(0205)      DO 40 J=1,L4P1
(0206)      CALL STACK (J,L1,L4,N4,J4,N1,N2)
(0207)      M1 = N1(J)
(0208)      DO 36 I=1,4
(0209) 36    UO(M1,I)=0
(0210)      M2 = N2(J)+1
(0211)      DO 39 K=M1,M2
(0212)      K3 = K-J4
(0213)      IF (K.NE.M1.OR.K.EQ.1) GOTO 37
(0214)      UO(K,1) = UO(K,1)-W4(J4)
(0215)      UO(K,2) = UO(K,2)+W4(J4)*Y4(J4)
(0216)      P4(J4) = P4(J4)/386.4

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(0217)      T4(J4) = T4(J4)/386.4
(0218) 37    IF (M3.NE.K3) GO TO 39
(0219)      U0(K,1) = U0(K,1)-W(J3)
(0220)      U0(K,2) = U0(K,2)+W(J3)*Y(J3)
(0221)      P(J3) = P(J3)/386.4
(0222)      T(J3) = T(J3)/386.4
(0223)      J3 = J3+1
(0224)      IF (L3 GE J3) M3 = N3(J3)
(0225) 39    IF (K.LT.M2) CALL STAT(J4,K)
(0226) 40    CONTINUE
(0227)      IF (L5.EQ.0) GOTO 100
(0228)      IF (L5.LT.2) GO TO 12
(0229)      C
(0230)      C      CALCULATE STATIC BEARING LOADS
(0231)      C
(0232)      DO 43 L=1,L5
(0233)      READ (KR,8001) L0,N5(L),D5(L,1),D5(L,2),S5(L,1),S5(L,2)
(0234)      +,T5(L,1),T5(L,2)
(0235) 43    CONTINUE
(0236)      DO 75 K=1,2
(0237)      DO 75 K1=1,4
(0238)      KK3 = KFCN(4,K,K1)
(0239)      DO 75 K2=1,2
(0240)      KK4 = KFCN(2,K,K2)
(0241)      K3 = K1-2
(0242)      IF (K2 EQ K3) GO TO 72
(0243)      P9 = 0
(0244)      GO TO 75
(0245) 72    P9 = 1
(0246) 75    A5(1, KK3, KK4) = P9
(0247)      M3 = 0
(0248)      IF (L3 EQ 0) GO TO 61
(0249)      M3 = N3(1)
(0250)      J3 = 1
(0251) 61    L8 = 1
(0252)      M5 = N5(L8)
(0253)      DO 90 J=1,L4P1
(0254)      CALL JFCN (J,M1)
(0255)      DO 51 K1=1,8
(0256) 51    V0(M1,K1) = 0
(0257)      IF (J.EQ.1) GO TO 70
(0258)      V0(M1,1) = -W4(J4)
(0259)      V0(M1,2) = W4(J4)*Y4(J4)
(0260)      ISTEP = 2
(0261)      CALL STEP (M2,ISTEP,IER)
(0262)      IF (IER.EQ.1) GO TO 9999
(0263) 70    CALL MFCN(J,M21,M2)
(0264)      WRITE (KW, 9998)
(0265)      DO 90 K0=M1,M2
(0266)      K4 = K0-J4
(0267)      IF (M3.NE.K4) GO TO 76
(0268)      V0(K0,1) = V0(K0,1)-W(J3)
(0269)      V0(K0,2) = V0(K0,2)+W(J3)*Y(J3)
(0270)      J3 = J3+1

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(0271)      IF (L3.GE.J3) M3 = N3(J3)
(0272)  76   IF (M5 NE K4) GO TO 82
(0273)      WRITE (KW, 9998)
(0274)      DO 32 K=1,2
(0275)      IF (S5(LB,K).GT.0) GO TO 32
(0276)      WRITE(KW,5000)
(0277)  5000 FORMAT (T10,40HBRG STIFFNESS IS DEFAULTED TO 0.1 LB/IN )
(0278)      S5(LB,K) = 0.1
(0279)  32   CONTINUE
(0280)      ISTEP = 3
(0281)      CALL STEP (K0,ISTEP,IER)
(0282)  82   IF (K0 GT.M21) GO TO 90
(0283)      ISTEP = 1
(0284)      CALL STEP (K0,ISTEP,IER)
(0285)  90   CONTINUE
(0286)      DO 99 K=1,2
(0287)      K11 = KFCN(4,K,1)
(0288)      K12 = KFCN(4,K,2)
(0289)      K21 = KFCN(2,K,1)
(0290)      K22 = KFCN(2,K,2)
(0291)      K13 = KFCN(4,K,3)
(0292)      K14 = KFCN(4,K,4)
(0293)      P9 = A5(M2,K11,K21)*A5(M2,K12,K22)
(0294)      P9 = P9-A5(M2,K11,K22)*A5(M2,K12,K21)
(0295)      C5(2,1) = A5(M2,K12,K21)*V0(M2,K11)-A5(M2,K11,K21)*V0(M2,K12)
(0296)      C5(2,1) = C5(2,1)/P9
(0297)      P9 = (A5(M2,K11,K22)*V0(M2,K12)-A5(M2,K12,K22)*V0(M2,K11))/P9
(0298)      DO 95 L=1,L4P1
(0299)      L6 = L4+2-L
(0300)      IF (L.GT.1) GO TO 94
(0301)  93   C5(1,L6) = P9
(0302)      GOTO 95
(0303)  94   J1 = L6-1
(0304)      K32 = KFCN(3,K,2)
(0305)      K33 = KFCN(3,K,3)
(0306)      P9 = A6(J1,K32)*C5(2,1)+A6(J1,K33)*P9
(0307)      GO TO 93
(0308)  95   CONTINUE
(0309)      L = 0
(0310)      DO 99 J=1,L4P1
(0311)      CALL JFCN (J,M1)
(0312)      M2 = M2(J)+1
(0313)      IF (M1.GT.1) C5(2,J) = V0(M1,K14)
(0314)      DO 99 K0=M1,M2
(0315)      K4 = K0-J4
(0316)      IF (K0.EQ.1) GO TO 71
(0317)  97   IF (M5 NE K4) GO TO 99
(0318)      X5(L,K) = D5(L,K)-V0(K0,K14)
(0319)      Y5(L,K) = V0(K0,K13)
(0320)      DO 98 K2=1,2
(0321)      KK4 = KFCN(2,K,K2)
(0322)      X5(L,K) = X5(L,K)-A5(K0,K14,KK4)*C5(K2,J)
(0323)  98   Y5(L,K) = Y5(L,K)+A5(K0,K13,KK4)*C5(K2,J)
(0324)      W5(L,K) = S5(L,K)*X5(L,K)

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(0325)      Q5(L,K) = T5(L,K)*Y5(L,K)
(0326)  71   IF (L.EQ.L5) GO TO 99
(0327)      L = L+1
(0328)      M5 = N5(L)
(0329)      GOTO 97
(0330)  99   CONTINUE
(0331)      WRITE (KW,5001)
(0332)  5001 FORMAT(/93H BRG ST LOCATION *****VERTICAL PLANE*****
(0333)      +* *****HORIZONTAL PLANE*****/1X,2(5H NO.),3X,4H(IN),3X,
(0334)      +2(35H MISALGN(IN) LOAD(LB) MOM(IN-LB)))
(0335)      DO 41 L=1,L5
(0336)      N = N5(L)
(0337)  41   WRITE(KW,9002) L,N,Z(N), (D5(L,K),W5(L,K),Q5(L,K),K=1,2)
(0338)  9002 FORMAT(2I5,F10.4,2(F11.6,2F11.4,2X))
(0339)      P9 = 0
(0340)      Q = 0
(0341)      DO 42 L=1,L4P1
(0342)      M2 = N2(L)+1
(0343)      P9 = P9-U0(M2,1)
(0344)  42   Q = Q-U0(M2,2)
(0345)      Z0 = Z(L+1)-Q/P9
(0346)      WRITE (KW,5002) P9,Z0
(0347)  5002 FORMAT(/T15,12HTOTAL WEIGHT,T33,1H=,1PE11.4,5H (LB)/
(0348)      +T15,19HLOCATION OF C.G. =,E11.4,5H (IN))
(0349)      WRITE (KW,5003) NCASE
(0350)  5003 FORMAT(28H1NUMBER OF SPEED GROUPS =,I5)
(0351)  C
(0352)  C   SETUP OUTPUT LOGIC
(0353)  C
(0354)  100  NTORS=0
(0355)      NBEND=0
(0356)      S = 0
(0357)      IF (J8.EQ.0) GO TO 120
(0358)      READ (KR,8000) (N8(I),I=1,J8)
(0359)      READ (KR,8000) (K8(I),I=1,J8)
(0360)      DO 112 I=1,J8
(0361)      K8I = K8(I)
(0362)      GO TO (112,113,115,115,113,113,114,113), K8I
(0363)  113  NTORS = NTORS+1
(0364)      KTORS(NTORS) = N8(I)
(0365)      GO TO (112,112,112,112,115,115,112,114), K8I
(0366)  114  NBEND = NBEND+1
(0367)      KBEND(NBEND) = N8(I)
(0368)  115  NBEND = NBEND+1
(0369)      KBEND(NBEND) = N8(I)
(0370)  112  CONTINUE
(0371)  120  CONTINUE
(0372)      IF (I5.EQ.2) NTORS = 0
(0373)      WRITE(10) NCASE,NTORS,NBEND
(0374)      IF (I5-2) 101,102,103
(0375)  101  WRITE (KW,5007)
(0376)  5007 FORMAT (39H DYNAMIC RESPONSE OF THE TORSIONAL MODE)
(0377)      GO TO 104
(0378)  102  WRITE (KW,5008)

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(0379) 5008 FORMAT(37H DYNAMIC RESPONSE OF THE BENDING MODE)
(0380) GO TO 104
(0381) 103 WRITE(KW,5009)
(0382) 5009 FORMAT(54H DYNAMIC RESPONSES OF BOTH TORSIONAL AND BENDING MODES)
(0383) 104 CONTINUE
(0384) DO 126 ICASE=1,NCASE
(0385) WRITE (KW,6030) ICASE
(0386) 6030 FORMAT (////19H SPEED GROUP NUMBER,15/)
(0387) READ (KR,8000) LRUN
(0388) PC = .1047197551197
(0389) PCC = 60*PC
(0390) IF (LTYP.EQ.1) LRUN = 0
(0391) READ(KR,8001) I7,IFRE,SPE1,SPE2
(0392) IF(NBEND.GT.0) GO TO 1203
(0393) I7=1
(0394) SPE1=0.0
(0395) 1203 CONTINUE
(0396) WRITE(10) IDENT,TITLE,I7,L5,L1P,KRUN,LRUN
(0397) IF(I7.GT.1) GO TO 1201
(0398) SRAT=1.0
(0399) GO TO 1202
(0400) 1201 SRAT=(SPE2/SPE1)**(1./(I7-1))
(0401) 1202 S0=SPE1/SRAT
(0402) I6=1
(0403) DO 125 JSPD=1,I7
(0404) S0=S0*SRAT
(0405) S00(JSPD)=S0
(0406) CONTINUE
(0407) IF (NTORS.GT.0) WRITE (10) (KTORS(I),I=1,NTORS)
(0408) IF (NBEND.GT.0) WRITE (10) (KBEND(I),I=1,NBEND)
(0409) IF (I5.EQ.1) GO TO 111
(0410) IF (L5.EQ. 0) GO TO 106
(0411) DO 105 L=1,4
(0412) IF (ICASE.GT.1.OR.JSPD.GT.1) GO TO 1050
(0413) JBRG(L) = L
(0414) IF (L.GT.L5) GO TO 105
(0415) N = N5(L)
(0416) ZBRG(L) = Z(N)
(0417) 1050 IF (I6.EQ.0.OR.L.GT.L5) GO TO 105
(0418) READ (KR,8001) L0,I6,XS(L,1),XS(L,2)
(0419) IF(I6.EQ.1 .OR. L.EQ.L5) GO TO 105
(0420) WRITE(KW,8004)
(0421) 8004 FORMAT(///46H I6 MUST BE UNITY EXCEPT FOR THE LAST BEARING.)
(0422) GO TO 9999
(0423) 105 CONTINUE
(0424) WRITE(10) (N5(L),(XS(L,I),I=1,2),L=1,L5)
(0425) IF (L5.EQ.0) GO TO 106
(0426) DO 106 L=1,L5
(0427) XSS(L,1,JSPD)=XS(L,1)
(0428) XSS(L,2,JSPD)=XS(L,2)
(0429) 106 CONTINUE
(0430) S00 = PC*S0
(0431) S = S0
(0432) SS = S00

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(0433)      IF (L3.EQ.0) GO TO 109
(0434)      DO 108 L=1,L3
(0435) 108   PS(L) = P(L)*SS
(0436) 109   IF(L4.EQ.0) GO TO 111
(0437)      DO 110 L=1,L4
(0438) 110   P4S(L)=P4(L)*SS
(0439) 111   CONTINUE
(0440)      IF(LRUN.EQ.0) GO TO 1205
(0441)      IFRE=1
(0442)      JFQ(1)=1
(0443)      FREQ(1,1)=S0/60.0
(0444)      GO TO 1208
(0445) 1205  DO 1103 L=1,IFRE
(0446)      READ (KR,8001) L0,I8,FREQ1,FREQ2
(0447)      JFQ(L)=I8
(0448)      IF(I8.EQ.1) GO TO 1206
(0449)      FRAT=(FREQ2/FREQ1)**(1./(I8-1))
(0450)      GO TO 1207
(0451) 1206  FRAT=1.0
(0452) 1207  FRQY=FREQ1/FRAT
(0453)      DO 1101 I=1,I8
(0454)      FRQY=FRQY*FRAT
(0455) 1101  FREQ(L,I)=FRQY
(0456) 1103  CONTINUE
(0457) 1208  WRITE(10) IFRE
(0458)      DO 1209 L=1,IFRE
(0459)      JFK=JFQ(L)
(0460)      WRITE(10) JFK
(0461)      IF (LRUN.EQ.0) WRITE(KW,5011) L,(FREQ(L,I),I=1,JFY)
(0462) 5011  FORMAT(/27H EXCITATION FREQUENCY GROUP,15/5H HZ ,11F10.4)
(0463)      IF(LIST.EQ.2) GO TO 1209
(0464)      IF (LTP.EQ.1) GO TO 1104
(0465)      IF(JSPD.EQ.1.OR.(L.EQ.1.AND. IFRE.GT.1))WRITE(KW,5012)
(0466) 5012  FORMAT (/23H      SPEED      FREQUENCY,8X,16HEND DETERMINANTS/4X,
(0467)      +5H(RPM),7X,4H(HZ),6X,28HCO-ROTATIONAL CTR-ROTATIONAL)
(0468) 1104  CALL ENDST(S,NTORS,NBEND,JFK,L)
(0469)      IF (LRUN.EQ.1) GO TO 1209
(0470)      IF (LTP-2) 1111,1209,1113
(0471) 1111  WRITE (KW,5021)
(0472) 5021  FORMAT (1H1)
(0473)      GO TO 1113
(0474) 1113  WRITE (KW,5023)
(0475) 5023  FORMAT (/1H )
(0476) 1115  WRITE (KW,5013)
(0477) 5013  FORMAT (11H FREQUENCY,5X,9HTORSIONAL/4X,4H(HZ) 8X,9HEND STIFF
(0478)      DO 117 I=1,JFK
(0479)      WRITE (KW,5014) FREQ(L,I),TORD(L,I)
(0480) 117   CONTINUE
(0481) 5014  FORMAT (1PD12.4,D15.6)
(0482) 1209  CONTINUE
(0483) 125   CONTINUE
(0484)      IF (LPRI.EQ.-1) GO TO 1106
(0485)      WRITE (KW,5004) (JBRG(L),L=1,4),(NS(L),L=1,LS)
(0486) 5004  FORMAT (/27H BRG NO,I18,3I24/7H STN NO,I18,3I24

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(0487)      WRITE (KW,5005) (ZBRG(L),L=1,L5)
(0488) 5005  FORMAT (9H LOC (IN),1PE15.4,3(12X,E12.4))
(0489)      WRITE (KW,5006)
(0490) 5006  FORMAT (9H      SPEED,3X,4(4X,3HRAD,9X,3HANG,5X)/
(0491)      +4X,9H(RPM)      ,4(3X,21H(LB/IN)      (IN-LB/RAD)))
(0492)      DO 1051 II=1,17
(0493) 1051  WRITE (KW,5010) S00(II),((XSS(L,I,II),I=1,2),L=1,L5)
(0494) 5010  FORMAT (1P11E12.4)
(0495) 1106  CONTINUE
(0496) 126   CONTINUE
(0497)      IF(KRUN.EQ.0.OR.LIST.EQ.2) GO TO 9999
(0498) 4321  REWIND 10
(0499)      CALL SYDSYN
(0500) 9999  CALL EXIT
(0501)      END

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(0502) SUBROUTINE ENDST(S,NTORS,NBEND,JFK,I9)
(0503) INTEGER TITLE(16)
(0504) COMMON/AMH/F,FF,XS(4,2),F1,FF1,SS
(0505) COMMON/AVIB/AA5(80,8,4)
(0506) COMMON/ATEST1/B1(75),B2(75),B3(75),B4(75),B5(75),B6(75)
(0507) COMMON/ATEST2/UO(80,4)
(0508) COMMON/BSTEP/D5(4,2)
(0509) COMMON/CSTAT/X(75),Z(76)
(0510) COMMON/ACOU/S4(4),A6(4,6)
(0511) COMMON/AHIN/C4(4),W4(4),P4(4),T4(4),Y4(4)
(0512) COMMON/AREND/U(80,2),ZH(76),ZK(20),FFRT
(0513) COMMON/BNODE/W(76),P(76),T(76),Y(76)
(0514) COMMON/VHODE/PS(76)
(0515) COMMON/VHIN/P4S(4)
(0516) COMMON/AFREQ/FREQ(5,11),PCC,JFQ(5),IFRE
(0517) COMMON/TORL/TORD(5,11)
(0518) COMMON/MO/AMAX(4),QC5(80,8),QU(80,8,2)
(0519) COMMON/IHIN/N1(5),N2(5)
(0520) COMMON/ANODE/N3(76)
(0521) COMMON/ABEND/L1P,L4P1,I8,I5
(0522) COMMON/AINT/N8(76),K8(76),J8
(0523) COMMON/CHEAD1/TITLE,L1,L2,L3,L4,L5,LIST/WR/KW,KR
(0524) COMMON/ASTEP/J4,LB,M5,N5(4)
(0525) COMMON/AINER/TRA(75)
(0526) DIMENSION AM(4,4),BM(4,4),AMI(4,4),UU(80,8,2),XD5(80,8),XV(4,2)
(0527) DIMENSION DET(2),TRATE(76),K9(20)
(0528) DIMENSION B(10),AI(4,2,2),E(4),P4F(4),PF(80),VV(80,2)
(0529) EQUIVALENCE (UU(1),VV(1))
(0530) IONE = 1
(0531) ITWO = 2
(0532) IFOUR = 4
(0533) IF (NBEND.EQ.0) GO TO 245
(0534) JMAX = 4
(0535) CSPD=S/60
(0536) SS=CSPD*PCC
(0537) NEND = 2*NBEND
(0538) 245 CONTINUE
(0539) DO 1000 I=1,JFK
(0540) F=FREQ(I9,I)
(0541) FF = F*PCC
(0542) F2 = FF*FF
(0543) C
(0544) C CALCULATE TORSIONAL RESPONSE
(0545) C
(0546) M8 = 0
(0547) LL8 = 0
(0548) L8 = 1
(0549) IF (NTORS.GT.0) WRITE(10) F
(0550) IF (J8.EQ.0) GO TO 31
(0551) ITORS = 0
(0552) M8 = M8(1)
(0553) KK8 = K8(1)
(0554) 31 L81 = L8
(0555) IF (I5.EQ.2) GO TO 400

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(0556)      IF( ITORS.GT.0 ) GO TO 300
(0557)  C *** INITIALIZE HOMOGENEOUS SOLUTION
(0558)      U(1,1) = 0
(0559)      U(1,2) = 1
(0560)  300   M3 = 0
(0561)      IF (NTORS.EQ.0) GO TO 320
(0562)      GO TO (310,320,310,310,320,320,310,320), KK8
(0563)  310   IF (J8.LE.L8) GO TO 99
(0564)      L8 = L8 +1
(0565)      KK8=K8(L8)
(0566)      GO TO (310,315,310,310,315,315,310,315), KK8
(0567)  315   L81 = L8
(0568)  C *** IDENTIFY TORSIONAL EXCITATION STATIONS
(0569)      M8=N8(L8)
(0570)  320   IF (L3.EQ.0) GO TO 1
(0571)      M3 = M3(1)
(0572)      J3 = 1
(0573)  C *** INTEGRATION OF THE TORSIONAL PROBLEM
(0574)  1      DO 4 L=1,L4P1
(0575)      CALL JFCN(L,M1)
(0576)      IF (L.EQ.1) GO TO 2
(0577)      IF( ITORS.GT.0 ) GO TO 32
(0578)      P4F(J4) = F2*P4(J4)
(0579)      U(M1,1) = U(M2,1)-P4F(J4)*U(M2,2)
(0580)      U(M1,2) = U(M2,2)+C4(J4)*U(M1,1)
(0581)  32     IF (LL8.EQ.0) GO TO 2
(0582)      VV(M1,1) = VV(M2,1)-P4F(J4)*VV(M2,2)
(0583)      VV(M1,2) = VV(M2,2)+C4(J4)*VV(M1,1)
(0584)  2      CALL MFCN(L,M21,M2)
(0585)      DO 4 K=M1,M2
(0586)      K4 = K-J4
(0587)      IF (J8.EQ.0) GO TO 33
(0588)      IF (K4.NE.M8) GO TO 33
(0589)      GO TO (33,87,33,33,87,87,33,87), KK8
(0590)  87     L82 = L81
(0591)      L81 = L81+1
(0592)      IF (L81.LE.J8) M8 = N8(L81)
(0593)      IF (L82.NE.L8) GO TO 33
(0594)      MM9 = K4
(0595)      KK8 = 1
(0596)      MM8 = K
(0597)      LL8 = 1
(0598)  C *** INITIALIZE PARTICULAR SOLUTION
(0599)      VV(K,1) = -1
(0600)      VV(K,2) = 0
(0601)  33     IF (M3.NE.K4) GO TO 3
(0602)      IF( ITORS.GT.0 ) GO TO 34
(0603)      PF(J3) = F2*P(J3)
(0604)      U(K,1) = U(K,1)-PF(J3)*U(K,2)
(0605)  34     IF (LL8.EQ.0) GO TO 35
(0606)      VV(K,1) = VV(K,1)-PF(J3)*VV(K,2)
(0607)  35     J3 = J3+1
(0608)      IF (L3.GE.J3) M3 = M3(J3)
(0609)  3      IF (K.GT.M21) GO TO 4

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(0610)      KP = K+1
(0611)      IF( ITORS.GT.0 ) GO TO 36
(0612)      B(1) = U(K,1)
(0613)      B(2) = U(K,2)
(0614)      CALL TORS (K,B)
(0615)      U(KP,1) = B(1)
(0616)      U(KP,2) = B(2)
(0617) 36   IF (LL8.EQ.0) GO TO 4
(0618)      B(1) = VV(K,1)
(0619)      B(2) = VV(K,2)
(0620)      CALL TORS (K,B)
(0621)      VV(KP,1) = B(1)
(0622)      VV(KP,2) = B(2)
(0623) 4     CONTINUE
(0624)      IF( ITORS.GT.0 ) GO TO 46
(0625)  C *** END EXCITATION RESPONSE
(0626)      ZE = U(M2,1)
(0627)      TORD(19,1) = ZE
(0628)      YE=ZE
(0629)      IF (U(M2,2).NE.0) GO TO 7
(0630)      IF (I5.EQ.1)
(0631)      +WRITE (KW,5002) F
(0632) 5002  FORMAT (26H1END NODE IS STATIONARY AT,1PE12.4,3H H2/9H TORS STI,
(0633)      +52HFF BELOW IS END TORQUE PER UNIT TWIST OF FIRST NODE./1H )
(0634)      GOTO 8
(0635) 7     ZE = ZE/U(M2,2)
(0636)      IF (I5.EQ.1)
(0637)      +WRITE (KW,5006)
(0638) 5006  FORMAT (1H1)
(0639) 8     DO 5 L=1,L4P1
(0640)      CALL JFCN (L,M1)
(0641)      M2 = N2(L)+1
(0642)      DO 5 K=M1,M2
(0643)      IF (K.EQ.M1.AND.L.NE.1) GO TO 5
(0644)      K4 = K-J4
(0645)      ZM(K4) = U(K,2)
(0646)      IF (K4.LT.L1P) BBB = B5(K4)
(0647)      TRATE(K4)=U(K,1)/YE/BBB
(0648) 5     CONTINUE
(0649)      CALL MODE
(0650)      IF(NTORS.GT.0) WRITE(10) (ZM(K4),K4=1,L1P)
(0651)      IF (I5.NE.1) GO TO 9
(0652)      WRITE (KW,5007) F,L1P,Z(L1P),ZE
(0653) 5007  FORMAT (13H FREQUENCY =,1PE12.4,3H H2/13H NODE NO =,I3/
(0654)      +13H LOCATION =,1PE12.4,3H IN/13H TORS STIFF =,1PE12.4,
(0655)      +10H IN-LB/RAD/1H )
(0656)      WRITE (KW,5013)
(0657) 5013  FORMAT (T15,8HLOCATION,T31,8HRELATIVE,T49,4HUNIT/T3,4HNODE,T17,
(0658)      +4H(IN),T32,5HTWIST,T46,10HTWIST RATE/1H )
(0659)      DO 6 K=1,L1P
(0660) 6     WRITE (KW,5014) K,Z(K),ZM(K),TRATE(K)
(0661) 5014  FORMAT (15,2(1X,F15.4),7X,1PE11.4)
(0662)      KPAGE = 0
(0663) 9     IF(NTORS.EQ.0) GO TO 99

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(0664) C *** ASSIGNED EXCITATION RESPONSE
(0665) 46 IF (U(M2,1).EQ.0) GO TO 39
(0666) IF (V(M2,1).EQ.0) GO TO 38
(0667) VU = V(M2,1)
(0668) IF (U(MM8,2).EQ.0) GO TO 37
(0669) AA = U(MM8,2)
(0670) VU = VU*AA
(0671) GOTO 40
(0672) 37 IF (I5.EQ.1) WRITE(KW,5003) M8,F,M8
(0673) 5003 FORMAT (28HITORS EXCITATION AT NODE NO.,I3,18H CAUSES FORE-SEGMT,
(0674) +13H RESONANCE AT,1PD12.4,3H HZ/20H TORS STIFF BELOW IS,
(0675) +19H TORQUE AT NODE NO.,I3,24H PER UNIT TWIST OF FIRST,
(0676) +6H NODE./1H )
(0677) AA = 1
(0678) GOTO 41
(0679) 38 IF (I5.EQ.1) WRITE(KW,5004) M8,F,M8
(0680) 5004 FORMAT (28HITORS EXCITATION AT NODE NO.,I3,17H CAUSES AFT-SEGMT,
(0681) +13H RESONANCE AT,1PD12.4,3H HZ/20H TORS STIFF BELOW IS,
(0682) +19H TORQUE AT NODE NO.,I3,23H PER UNIT TWIST OF LAST,
(0683) +6H NODE./1H )
(0684) KU = 2
(0685) ZK(L8) = 1/V(M2,2)
(0686) GOTO 42
(0687) 39 IF (I5.EQ.1) WRITE (KW,5005) F
(0688) 5005 FORMAT (27HITORS RESONANCE IS FOUND AT,1PD12.4,3H HZ/1H )
(0689) KU = 3
(0690) GO TO 90
(0691) 40 IF (I5.NE.1.OR.KPAGE.NE.0) GO TO 41
(0692) KPAGE = 1
(0693) WRITE (KW,5006)
(0694) 41 IF (KPAGE.NE.0.AND.I5.EQ.1) WRITE (KW,5008)
(0695) 5008 FORMAT (/1H )
(0696) ZK(L8) = -U(M2,1)/VU
(0697) KU = 1
(0698) 42 AMP = -V(M2,1)/U(M2,1)
(0699) IF (I5.NE.1) GO TO 90
(0700) WRITE (KW,5007) F,MM9,Z(MM9),ZK(L8)
(0701) 90 JTORS = 0
(0702) IF (I5.EQ.1) WRITE(KW,5013)
(0703) MM8 = M8(1)
(0704) KK8 = K8(1)
(0705) JJ8 = 1
(0706) DO 43 L=1,L4P1
(0707) CALL JFCN (L,M1)
(0708) M2 = M2(L)+1
(0709) DO 43 K=M1,M2
(0710) K4 = K-J4
(0711) IF (L.GT.1.AND.K.EQ.M1) GO TO 43
(0712) IF (K4.NE.MM8) GO TO 43
(0713) IF (KU.NE.3) GO TO 89
(0714) BB=ZM(K4)
(0715) GO TO 890
(0716) 89 BB = 0
(0717) TRATE(K4) = 0

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(0718)      IF (KU.NE.1) GO TO 891
(0719)      BB = BB+U(K,2)/AA
(0720)      IF (L.LT.L4P1.OR.K.LT.M2) TRATE(K4) = TRATE(K4)+U(K,1)*AMP
(0721)  891  IF (MM8.GE.K) GO TO 892
(0722)      BB = BB+2K(L8)*VV(K,2)
(0723)      IF (L.LT.L4P1.OR.K.LT.M2) TRATE(K4) = TRATE(K4)+VV(K,1)
(0724)  892  TRATE(K4) = TRATE(K4)/B5(K4)
(0725)  890  IF (I5.EQ.1) WRITE(KU,5014) K4,Z(K4),BB,TRATE(K4)
(0726)      GO TO (94,93,94,94,93,93,94,93), KK8
(0727)  93   JTORS = JTORS+1
(0728)      IF (KU.NE.3) GO TO 91
(0729)      GG = ZH(K4)
(0730)      GO TO 92
(0731)  91   GG = AMP*U(K,2)
(0732)      IF (MM8.LT.K) GG = GG+VV(K,2)
(0733)  92   VV(JTORS,2) = GG
(0734)  94   IF (JJ8.EQ.J8) GO TO 44
(0735)      JJ8 = JJ8+1
(0736)      NN8 = N8(JJ8)
(0737)      KK8 = K8(JJ8)
(0738)  43   CONTINUE
(0739)  44   ITORS = ITORS+1
(0740)      IF (NTORS.GT.0) WRITE(10) KU,(VV(L,ITWO),L=1,NTORS)
(0741)      IF (ITORS.EQ.NTORS) GO TO 99
(0742)  C *** NEXT EXCITATION STATION
(0743)      L8 = L8+1
(0744)      KK8 = K8(L8)
(0745)      L81 = L8
(0746)      M8 = N8(L8)
(0747)      LL8 = 0
(0748)      GO TO 300
(0749)  C
(0750)  C   CALCULATE BENDING RESPONSE
(0751)  C
(0752)  99   IF (I5.EQ.1) GO TO 1000
(0753)      L8=1
(0754)      LL8 = 0
(0755)      IF (I5.EQ.1) GO TO 216
(0756)      L81 = L8
(0757)  400  L83 = 1
(0758)      L84 = 1
(0759)      IF (J8.EQ.0) GO TO 10
(0760)      M8 = N8(L8)
(0761)      KK8 = K8(L8)
(0762)      IF (NBEND.GT.0) WRITE(10) F,CSPD
(0763)      IBEND = 0
(0764)  10   IF (L8.GT.1) GO TO 45
(0765)      FFRT = SQRT(FF)
(0766)      CALL BEND
(0767)  C *** INITIALIZE HOMOGENEOUS SOLUTION
(0768)      DO 12 K=1,2
(0769)      KB = 4*K
(0770)      KB1 = 9-KB
(0771)      KB4 = KB1+3

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(0772)      DO 18 KBO=KB1,KB4
(0773)      DO 18 K1=1,2
(0774)      LBO = KFCN(ITWO,K,K1)
(0775)  18   AA5(1,KBO,LBO) = 0
(0776)      DO 12 K1=1,4
(0777)      KK3 = KFCN(IFOUR,K,K1)
(0778)      DO 12 K2=1,2
(0779)      KK4 = KFCN(ITWO,K,K2)
(0780)      K3 = K1-2
(0781)      IF (K2.EQ.K3) GO TO 11
(0782)      AA = 0
(0783)      GO TO 12
(0784)  11   AA = 1
(0785)  12   AA5(1,KK3,KK4) = AA
(0786)      DO 95 K1=1,2
(0787)      UU(1,1,K1)=0.0
(0788)  95   UU(1,2,K1)=1.0
(0789)  C *** START OF ASSIGNED EXCITATION RESPONSE
(0790)  45   JBEND = 0
(0791)  C *** START OF SENSE-OF-ROTATION CYCLE
(0792)  451  M3 = 0
(0793)      L85 = L8*L83*L84
(0794)      IF (L3.EQ.0) GO TO 13
(0795)      M3 = M3(1)
(0796)      J3 = 1
(0797)  13   M5 = 0
(0798)      LB = 1
(0799)      IF (L5.GT.0) M5 = M5(1)
(0800)  C *** INTEGRATION OF THE BENDING PROBLEM
(0801)      DO 20 J=1,L4P1
(0802)      CALL JFCN (J,M1)
(0803)      IF (J.EQ.1) GO TO 15
(0804)      IF (L8.GT.1.AND.LL8.EQ.0) GO TO 47
(0805)      CALL LUMP1 (W4(J4),Y4(J4),T4(J4),P4S(J4),FF,F2,AA,BB,CC,DD)
(0806)  47   IF (L85.GT.1) GO TO 48
(0807)      DO 16 K1=1,4
(0808)      DO 14 K=1,8
(0809)  14   B(K) = AA5(M2,K,K1)
(0810)      CALL LUMP (AA,BB,CC,DD,B)
(0811)      DO 16 K=1,8
(0812)  16   AA5(M1,K,K1) = B(K)
(0813)      CALL LIMP (M1,AM,BM)
(0814)      CALL COUP (M1,BM)
(0815)      DO 88 K1=1,2
(0816)  88   AI(J4,K,K1) = AM(K,K1)
(0817)  48   IF (LL8.EQ.0) GO TO 15
(0818)      DO 49 K=1,8
(0819)  49   B(K) = QU(M2,K,L83)
(0820)      CALL LUMP (AA,BB,CC,DD,B)
(0821)      CALL COUP1 (M1,J4,AI,B)
(0822)      DO 50 K=1,8
(0823)  50   QU(M1,K,L83) = B(K)
(0824)  15   CALL MFCN(J,M21,M2)
(0825)      DO 20 KO=M1,M2

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(0826)      K4 = K0-J4
(0827)      IF (J8.EQ.0) GO TO 56
(0828)      IF (K4.NE.M8.OR.KK8.LE.2) GO TO 56
(0829)      C *** IDENTIFY BENDING EXCITATION STATIONS
(0830)      L82 = L81
(0831)      L81 = L81+1
(0832)      IF (L81.LE.J8) M8 = M8(L81)
(0833)      IF (L82.NE.L8) GO TO 56
(0834)      K08 = K0
(0835)      K09 = K4
(0836)      LL8 = 1
(0837)      GO TO (356,356,52,53,52,53,51,51),KK8
(0838)      51  IF (L84.EQ.2) GO TO 53
(0839)      52  M88 = 1
(0840)      GO TO 54
(0841)      53  M88 = 2
(0842)      54  KK8 = 1
(0843)      C *** INITIALIZE PARTICULAR SOLUTION
(0844)      DO 55 K=1,2
(0845)      DO 55 K1=1,4
(0846)      K2 = KFCN(FOUR,K,K1)
(0847)      K3 = KFCN(TWO,K,K1)
(0848)      IF (K1.NE.M88.OR.L83.NE.K) GO TO 855
(0849)      AA = 1
(0850)      GO TO 955
(0851)      855  AA = 0
(0852)      955  IF (K1.LE.2) XV(K3,L83) = AA
(0853)      IF (K1.EQ.2.AND.M88.EQ.2) AA = -AA
(0854)      55  QU(K0,K2,L83) = AA
(0855)      356  IF (L8.GT.1.AND.LL8.EQ.0) GO TO 216
(0856)      56  IF (M3.NE.K4) GO TO 17
(0857)      IF (L8.GT.1.AND.LL8.EQ.0) GO TO 57
(0858)      CALL LUMP1 (W(J3),Y(J3),T(J3),PS(J3),FF,F2,AA,BB,CC,DD)
(0859)      57  IF (L85.GT.1) GO TO 601
(0860)      DO 59 K1=1,4
(0861)      DO 58 K=1,8
(0862)      58  B(K) = AA5(K0,K,K1)
(0863)      CALL LUMP (AA,BB,CC,DD,B)
(0864)      DO 59 K=1,8
(0865)      59  AA5(K0,K,K1) = B(K)
(0866)      601  IF (LL8.EQ.0) GO TO 62
(0867)      DO 60 K=1,8
(0868)      60  B(K) = QU(K0,K,L83)
(0869)      CALL LUMP (AA,BB,CC,DD,B)
(0870)      DO 61 K=1,8
(0871)      61  QU(K0,K,L83) = B(K)
(0872)      62  J3 = J3+1
(0873)      IF (L3.GE.J3) M3 = M3(J3)
(0874)      17  IF (M5.NE.K4) GO TO 19
(0875)      IF (L85.GT.1) GO TO 666
(0876)      DO 65 K1=1,4
(0877)      DO 64 K=1,8
(0878)      64  B(K) = AA5(K0,K,K1)
(0879)      B(K)=AA5(K0,K,K1)

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(0880)      B(1)=B(1)-XS(LB,1)*B(4)
(0881)      B(2)=B(2)+XS(LB,2)*B(3)
(0882)      B(5)=B(5)-XS(LB,1)*B(8)
(0883)      B(6)=B(6)+XS(LB,2)*B(7)
(0884)      DO 65 K=1,8
(0885) 65    AA5(K0,K,K1) = B(K)
(0886) 666    IF (LL8.EQ.0) GO TO 68
(0887)      DO 66 K=1,8
(0888) 66    B(K) = QU(K0,K,L83)
(0889)      B(1)=B(1)-XS(LB,1)*B(4)
(0890)      B(2)=B(2)+XS(LB,2)*B(3)
(0891)      B(5)=B(5)-XS(LB,1)*B(8)
(0892)      B(6)=B(6)+XS(LB,2)*B(7)
(0893)      DO 67 K=1,8
(0894) 67    QU(K0,K,L83) = B(K)
(0895) 68    IF (LB.EQ.L5) GO TO 19
(0896)      LB = LB+1
(0897)      M5 = M5(LB)
(0898) 19    IF (K0.GT.M21) GO TO 20
(0899)      IF (L8.GT.1 .AND. LL8.EQ.0) GO TO 957
(0900)      TRAH=0.5*TRA(K4)
(0901)      POLH=SS*TRA(K4)
(0902)      ALUMP = 0.0
(0903)      BLUMP = 0.0
(0904)      CALL LUMP(ALUMP,BLUMP,TRAH,POLH,FF,F2,AA,BB,CC,DD)
(0905) 957    IF (L85.GT.1) GO TO 6019
(0906)      DO 959 K1=1,4
(0907)      DO 958 K=1,8
(0908) 958    B(K)=AA5(K0,K,K1)
(0909)      CALL LUMP(AA,BB,CC,DD,B)
(0910)      DO 959 K=1,8
(0911) 959    AA5(K0,K,K1)=B(K)
(0912) 6019   IF (LL8.EQ.0) GO TO 962
(0913)      DO 960 K=1,8
(0914) 960    B(K)=QU(K0,K,L83)
(0915)      CALL LUMP(AA,BB,CC,DD,B)
(0916)      DO 961 K=1,8
(0917) 961    QU(K0,K,L83)=B(K)
(0918) 962    CONTINUE
(0919)      KP = K0+1
(0920)      IF (L8.GT.1.AND.LL8.EQ.0) GO TO 69
(0921)      CALL FLEX(K4,FFRT,E)
(0922) 69    IF (L85.GT.1) GO TO 72
(0923)      DO 71 K1=1,4
(0924)      DO 70 K=1,8
(0925) 70    B(K) = AA5(K0,K,K1)
(0926)      CALL CFLEX(K4,B,E)
(0927)      DO 71 K=1,8
(0928) 71    AA5(KP,K,K1) = B(K)
(0929) 72    IF (LL8.EQ.0) GO TO 20
(0930)      DO 73 K=1,8
(0931) 73    B(K) = QU(K0,K,L83)
(0932)      CALL CFLEX(K4,B,E)
(0933)      DO 74 K=1,8

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(0934) 74 QU(KP,K,L83) = B(K)
(0935) IF(L8.GT.1 .AND. LL8.EQ.0) GO TO 857
(0936) ALUMP = 0.0
(0937) BLUMP = 0.0
(0938) CALL LUMP1(ALUMP,BLUMP,TRAH,POLH,FF,F2,AA,BB,CC,DD)
(0939) 857 IF(L85.GT.1) GO TO 6018
(0940) DO 859 K1=1,4
(0941) DO 858 K=1,8
(0942) 858 B(K)=AA5(KP,K,K1)
(0943) CALL LUMP(AA,BB,CC,DD,B)
(0944) DO 859 K=1,8
(0945) 859 AA5(KP,K,K1)=B(K)
(0946) 6018 IF(LL8.EQ.0) GO TO 862
(0947) DO 860 K=1,8
(0948) 860 B(K)=QU(KP,K,L83)
(0949) CALL LUMP(AA,BB,CC,DD,B)
(0950) DO 861 K=1,8
(0951) 861 QU(KP,K,L83)=B(K)
(0952) 862 CONTINUE
(0953) KQ=K4+1
(0954) UU(KQ,1,1)=AA5(KP,4,1)
(0955) UU(KQ,2,1)=AA5(KP,4,2)
(0956) UU(KQ,1,2)=AA5(KP,8,3)
(0957) UU(KQ,2,2)=AA5(KP,8,4)
(0958) 20 CONTINUE
(0959) IF (L85.GT.1) GO TO 207
(0960) IF(LIST.EQ.0) WRITE(KW,5019) S,F
(0961) 5019 FORMAT (17H1BENDING RESPONSE//12H SPEED = ,1PD12.4,4H RPM,
(0962) +12H FREQUENCY = ,1PD12.4,3H HZ/1H )
(0963) JORB = 0
(0964) IF(S.NE.0.0) GO TO 9226
(0965) NGYRO = 1
(0966) GO TO 9227
(0967) 9226 NGYRO = 2
(0968) C *** ISOTROPIC END DETERMINANT CHECK
(0969) 9227 DO 9222 N=1,2
(0970) NN = 2*(N-1)
(0971) DO 9221 J=1,2
(0972) JJ = 2*NN+J
(0973) DO 9221 K=1,2
(0974) KK = NN+K
(0975) 9221 AM(J,K) = AA5(M2,JJ,KK)
(0976) IMAXA = 2
(0977) IMAXB = 0
(0978) CALL MAXIV(AM,IMAXA,BN,IMAXB,DETERM,JMAX)
(0979) DET(N)=DETERM
(0980) IF (IMAXA.NE.0) GO TO 21
(0981) WRITE (KW,5021) F
(0982) 5021 FORMAT(/30H BENDING RESONANCE IS FOUND AT,1PE12.4,4H HZ//)
(0983) C *** CALCULATE ISOTROPIC RESONANT MODE
(0984) JORB = N
(0985) 28 J=1
(0986) K1 = NN+1
(0987) K2 = NN+2

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(0988) 23 J1 = NN+J
(0989) J2 = NN+J1
(0990) IF (AA5(M2,J2,K1).EQ.0.0) GO TO 24
(0991) E(K1) = -AA5(M2,J2,K2)/AA5(M2,J2,K1)
(0992) E(K2) = 1
(0993) GO TO 9222
(0994) 24 IF (AA5(M2,J2,K2).EQ.0.0) GO TO 25
(0995) E(K1) = 1
(0996) E(K2) = 0
(0997) GO TO 9222
(0998) 25 IF (J.EQ.2) GO TO 26
(0999) J = 2
(1000) GO TO 23
(1001) C *** INVERT ISOTROPIC END MATRIX
(1002) 21 DO 27 J=1,2
(1003) JJ = NN+J
(1004) DO 27 K=1,2
(1005) KK = NN+K
(1006) 27 AMI(JJ,KK) = AM(J,K)
(1007) IF (N.EQ.1) GO TO 28
(1008) WRITE (KW,5025) S,F,(DET(NWHIRL),NWHIRL=1,2)
(1009) 5025 FORMAT (1P2E12.4,2E15.6)
(1010) GO TO 28
(1011) 9222 CONTINUE
(1012) DO 76 N=1,L1P
(1013) DO 76 J=1,2
(1014) SHAPE=0.0
(1015) DO 75 K=1,2
(1016) K1=K
(1017) IF (J.EQ.2) K1=K1+2
(1018) 75 SHAPE=SHAPE+E(K1)*UU(N,K,J)
(1019) 76 UU(N,1,J)=SHAPE
(1020) WRITE(10) (DET(N),N=1,2),(Z(NU),(UU(NU,IONE,J),J=1,2),NU=1,L1P
(1021) GO TO 207
(1022) 26 WRITE (KW,5022)
(1023) 5022 FORMAT (21H END MATRIX IS EMPTY./1H )
(1024) CALL EXIT
(1025) 207 IF (LL8.EQ.0) GO TO 216
(1026) IF (L83.EQ.1.AND.L1ST.EQ.0) WRITE(KW,5107) S,F,K09
(1027) 5107 FORMAT (17H1BENDING RESPONSE//19H SPEED = ,1PD12.4,
(1028) +4H RPM//19H FREQUENCY = ,1PD12.4,3H HZ//
(1029) +19H ACTION NODE NO. = ,13)
(1030) DO 2081 K=1,4
(1031) 2081 AMAX(K) = 0
(1032) C *** CALCULATE ISOTROPIC INITIAL INFLUENCE COEFFICIENTS
(1033) NN=2*(L83-1)
(1034) DO 9225 J=1,2
(1035) JA = NN+J
(1036) JB = 5-JA
(1037) E(JA) = 0.0
(1038) IF (JORB.EQ.L83) GO TO 9225
(1039) DO 29 K=1,2
(1040) KA = NN+K
(1041) KB = NN+KA

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(1042) 29      E(JA) = E(JA) - AMI(JA,KA)*QU(M2,KB,L83)
(1043) 9225    E(JB) = 0.0
(1044) C ***  GENERATE COUPLING STATION INFLUENCE COEFFICIENTS
(1045)        DO 211 L=1,L4P1
(1046)        L6 = L4P1-L+1
(1047)        M2 = N2(L6)+1
(1048)        IF (L.EQ.1) GO TO 210
(1049)        BM(1,1) = QC5(M1,4) - AA5(M2,4,2)*E(2) - AA5(M2,4,4)*E(4)
(1050)        BM(2,1) = QC5(M1,8) - AA5(M2,8,2)*E(2) - AA5(M2,8,4)*E(4)
(1051)        DO 209 K=1,2
(1052)        K4 = KFCN(FOUR,K,4)
(1053)        DO 209 J=1,2
(1054)        J1 = 2*J-1
(1055) 209     AM(K,J) = AA5(M2,K4,J1)
(1056)        IMAXA = 2
(1057)        IMAXB = 1
(1058)        CALL MAXIV(AM,IMAXA,BM,IMAXB,DETERM,JMAX)
(1059)        E(1) = BM(1,1)
(1060)        E(3) = BM(2,1)
(1061) 210     M1 = N1(L6)
(1062)        DO 211 K0=M1,M2
(1063)        DO 211 K=1,8
(1064)        QC5(K0,K) = 0
(1065)        DO 211 J=1,4
(1066) 211     QC5(K0,K) = QC5(K0,K) + AA5(K0,K,J)*E(J)
(1067) C ***  CALCULATE TOTAL ROTATIONAL SOLUTION
(1068)        DO 214 L=1,L4P1
(1069)        CALL JFCN(L,M1)
(1070)        M2 = N2(L)+1
(1071)        DO 214 K=M1,M2
(1072)        K4 = K-J4
(1073)        DO 213 N=1,4
(1074)        J = N+4
(1075)        AA = QC5(K,N)
(1076)        BB = QC5(K,J)
(1077)        IF(K.LT.K08) GO TO 212
(1078)        AA = AA+QU(K,N,L83)
(1079)        BB = BB+QU(K,J,L83)
(1080) 212     TRY = ABS(AA)+ABS(BB)
(1081)        UU(K,N,L83) = AA
(1082)        UU(K,J,L83) = BB
(1083) 213     IF(AMAX(N) LT TRY) AMAX(N) = TRY
(1084) 214     CONTINUE
(1085)        IF (L83.GT.NGYRO) GO TO 2211
(1086)        IF(LIST.EQ.1) GO TO 217
(1087)        WRITE (KW,5100)
(1088) 5100     FORMAT (//T22,10HFORCE (LB),T36,14HMOMENT (IN-LB))
(1089)        WRITE (KW,5101) (XV(K,L83),K=1,4)
(1090) 5101     FORMAT (15H CO -ROTATIONAL,2(4X,1PD12.5)/
(1091)        +15H CTR-ROTATIONAL,2(4X,1PD12.5)/1H )
(1092)        WRITE (KW,5093) (AMAX(K),K=1,4)
(1093) 5093     FORMAT (T4,4HMODE,T19,5HSHEAR,T31,6HMOMENT,T43,5HSLOPE,T54,
(1094)        +10HDEFLECTION/10H VARIABLES,T19,5H(LBS),T31,7H(IN-LB),T57,
(1095)        +4H(IN)/6H SCALE,8X,1PD12.4/1H )

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(1096)      WRITE (KW,5023)
(1097) 5023  FORMAT (T9,8HLOCATION,21H CO-ROTATIONAL WHIRL,T72.20HCTR-ROTATION
(1098)      +AL WHIRL/14H NODE      (IN),2(53H SHEAR      MOMENT      SLOPE      D
(1099)      +EFLECTION M/(EI) )/1H )
(1100) 217  NN8=N8(1)
(1101)      JJ8 = 1
(1102)      DO 221 J=1,L4P1
(1103)      CALL JFCN (J,M1)
(1104)      M2 = N2(J)+1
(1105)      DO 221 K=M1,M2
(1106)      K4 = K-J4
(1107)      IF(K4.NE.NN8) GO TO 221
(1108)      DO 220 N=1,4
(1109)      L = N+4
(1110)      B(N) = UU(K,N,L83)/AMAX(N)
(1111) 220  B(L+1) = UU(K,L,L83)/AMAX(N)
(1112)      IF (J.LT.L4P1.OR.K.LT.M2) GO TO 250
(1113)      B(5) = 0
(1114)      B(10) = 0
(1115)      GO TO 251
(1116) 250  B(5) = UU(K,2,L83)/B2(K4)
(1117)      B(10) = UU(K,6,L83)/B2(K4)
(1118) 251  IF(LIST.EQ.0) WRITE(KW,5028) K4,Z(K4),(B(N),N=1,10)
(1119) 5028  FORMAT (14,F11.4,2(1X,OP4F10.6,1PD12.4))
(1120)      IF(JJ8.EQ.J8) GO TO 2211
(1121)      JJ8 = JJ8+1
(1122)      NN8 = N8(JJ8)
(1123) 221  CONTINUE
(1124) 2211 M8 = N8(L8)
(1125)      KK8 = K8(L8)
(1126)      IF (L83.EQ.2) GO TO 215
(1127) C *** SWITCH TO CTR-ROTATIONAL CASE
(1128)      L83 = 2
(1129)      LL8 = 0
(1130)      L81 = L8
(1131)      GO TO 451
(1132) C *** CARTESIAN REPRESENTATION
(1133) 215  IF(LIST.EQ.0) WRITE(KW,5102) S,F
(1134) 5102  FORMAT(/25H CARTESIAN REPRESENTATION//19H SPEED
(1135)      +1PE12.4,5H RPM //19H FREQUENCY      = ,E12.4,3H HZ)
(1136)      KKK8 = KK8
(1137)      WRITE(10) JORB,M8,KK8
(1138)      M=1
(1139)      DO 222 N=1,4
(1140) 222  AMAX(N) = 0
(1141)      DO 224 J=1,L4P1
(1142)      CALL JFCN (J,M1)
(1143)      M2 = N2(J)+1
(1144)      DO 224 K=M1,M2
(1145)      K4 = K-J4
(1146)      DO 223 N=1,4
(1147)      L = N+4
(1148)      AA = 0.0
(1149)      IF (JORB.NE.2) AA = AA+UU(K,N,1)

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(1150)      BB = 0.0
(1151)      IF(JORB.NE.1) BB=-UU(K,L,2)
(1152)      XD5(K,N) = (AA-BB)/2
(1153)      IF (M.EQ.2) XD5(K,N) = -XD5(K,N)
(1154)      TRY = (ABS(AA)+ABS(BB))/2
(1155)      IF (AMAX(N).LT.TRY) AMAX(N) = TRY
(1156) 223   XD5(K,L) = -(AA+BB)/2
(1157) 224   CONTINUE
(1158)      IF(LIST.EQ.1) GO TO 7002
(1159)      WRITE(KW,5103)
(1160) 5103   FORMAT(/37H STATION FORCE (LB)   MOMENT (IN-LB))
(1161)      WRITE(KW,5106) K09,(XV(J,M),XV(J,M),J=1,2)
(1162) 5106   FORMAT(I5,2(3X,1PE12.5))
(1163)      IF (JORB.NE.0) GO TO 7000
(1164)      WRITE (KW,5093) (AMAX(N),N=1,4)
(1165)      GO TO 7001
(1166) 7000   WRITE (KW,9999)
(1167) 9999   FORMAT (53H THE FOLLOWING ARE NORMALIZED RESONANT DISTRIBUTIONS./)
(1168) 7001   WRITE(KW,5104)
(1169) 5104   FORMAT (T9,29HLOCATION VERTICAL COMPONENTS,T72,21HHORIZONTAL COMP
(1170) +ONENTS/14H NODE      (IN),2(53H   SHEAR      MOMENT      SLOPE      DEF
(1171) +LECTION M/(EI) ))
(1172) 7002   NN8=N8(1)
(1173)      KK8 = K8(1)
(1174)      JJ8 = 1
(1175)      DO 226 J=1,L4P1
(1176)      CALL JFCN (J,M1)
(1177)      M2 = N2(J)+1
(1178)      DO 226 K=M1,M2
(1179)      K4 = K-J4
(1180)      IF (J.GT.1.AND.K.EQ.M1) GO TO 226
(1181)      IF (K4.NE.NN8) GO TO 226
(1182)      DO 225 N=1,4
(1183)      L = N+4
(1184)      B(N) = XD5(K,N)/AMAX(N)
(1185) 225     B(L+1) = XD5(K,L)/AMAX(N)
(1186)      IF (J.LT.L4P1.OR.K.LT.M2) GO TO 252
(1187)      B(5) = 0
(1188)      B(10) = 0
(1189)      GO TO 253
(1190) 252     B(5) = XD5(K,2)/B2(K4)
(1191)      B(10) = XD5(K,6)/B2(K4)
(1192) 253     IF(LIST.NE.1) WRITE(KW,5105) K4,Z(K4),(B(N),N=1,10)
(1193) 5105   FORMAT (I3,3H RE,F10.4,4F10 6,1PD12 4/6H      IM,63X,0P4F10 6,1PD12
(1194) +4)
(1195)      GO TO (260,260,231,232,231,232,231,231), KK8
(1196) 231     JBEND = JBEND+1
(1197)      K9(JBEND)=1
(1198)      LBEND = NBEND+JBEND
(1199)      ZM(JBEND) = XD5(K,4)
(1200)      ZM(LBEND) = XD5(K,8)
(1201)      IF (KK8.LT.7) GO TO 260
(1202) 232     JBEND = JBEND+1
(1203)      K9(JBEND)=2

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(1204)      LBEND = NBEND+JBEND
(1205)      ZM(JBEND) = XD5(K,3)
(1206)      ZM(LBEND) = XD5(K,7)
(1207)  260   IF (JJ8.EQ.J8) GO TO 227
(1208)      JJ8 = JJ8+1
(1209)      NN8 = N8(JJ8)
(1210)      KK8 = K8(JJ8)
(1211)  226   CONTINUE
(1212)  227   CONTINUE
(1213)      WRITE(10) (ZM(K),K=1,NBEND)
(1214)      IBEND = IBEND+1
(1215)      IF (KK8.LT.7.OR.L84.EQ.2) GO TO 244
(1216)  C *** SWITCH TO MOMENT EXCITATION
(1217)      L84 = 2
(1218)      L81 = L8
(1219)      M8 = N8(L8)
(1220)      KK8 = K8(L8)
(1221)      L83 = 1
(1222)      LL8 = 0
(1223)      GOTO 45
(1224)  244   IF (IBEND.EQ.NBEND) GO TO 100
(1225)  C *** IDENTIFY NEXT BENDING EXCITATION STATION
(1226)  216   LL8 = 0
(1227)  240   IF (J8.LE.L8) GO TO 100
(1228)      L8 = L8+1
(1229)      KK8 = K8(L8)
(1230)      IF (KK8.LT.3) GO TO 240
(1231)      L81 = L8
(1232)      L83 = 1
(1233)      L84 = 1
(1234)      M8 = N8(L8)
(1235)      GO TO 45
(1236)  100   CONTINUE
(1237)  1000  CONTINUE
(1238)      WRITE(10) (K9(I),I=1,NBEND)
(1239)      RETURN
(1240)      END

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(1241)      SUBROUTINE SYDSYN
(1242)      DIMENSION BRGLX(2,2),TLX(2,4),DXX(2,11),X(40,40)
(1243)      DIMENSION M8(20),K8(20)
(1244)      DIMENSION DETER(2,11)
(1245)      DIMENSION IWARN(2,11),NFORCE(20),KFORCE(20),BIG(20),SMALL(20)
(1246)      DIMENSION SLANT(20),PHASE(20),SPEED(11)
(1247)      DIMENSION FLX(4,20),PLX(80),WLX(80)
(1248)      DIMENSION IDENT(4),NTITLE(16),KEX(40)
(1249)      DIMENSION IRLAB(40),ICLAB(40),FREQ(11)
(1250)      DIMENSION BRGST(4,2),ENDET(2),SHAPE(76,3),STIF(2,2,20),
(1251)      +DAMP(2,2,20),KBG(4),POSIT(76)
(1252)      DIMENSION RET(11),XINT(11)
(1253)      DIMENSION TABLX(60,122)
(1254)      COMMON/BMAT/XLX(60,120),Y LX(60,120),ZLX(60,120),
(1255)      +XHALF(20,40),YHALF(20,40),ZHALF(20,40),QHALF(20,40)
(1256)      COMMON/BINV/XIN(60,122),XOU(60,122),DLX(2),IROW(61),ICOL(61)
(1257)      COMMON/WR/LW,LR
(1258)      COMMON/CBEG/IBEG
(1259)      COMMON/WUADD/FSQ
(1260)      COMMON/WUS/M8,K8,X,POSIT
(1261)      COMMON/CODA/K9(20)
(1262)      COMMON/WUSA/RET,XINT
(1263)      COMMON/PRMS/IRUN,ITYPE,IBRG,IDIAG
(1264)      COMMON/XGCON/SLOW,RLAX,IGEN
(1265)      DATA STIF,DAMP/160*0 0/
(1266)      M60 = 60
(1267)      JR = 1
(1268)      JC = 1
(1269)      KEEP=8
(1270)      KR=LR
(1271)      KW=LW
(1272)      KSAVE=9
(1273)      ISLO = 0
(1274)      READ (10) KASE,NTORS,NBEND
(1275)      IRUN = 0
(1276)      IF (NBEND.EQ 0.AND.NTORS.EQ 0) GO TO 5
(1277)      READ(KR,110) IRUN,ITYPE,IBRG,IPRI,IDIAG,IGEN,ISLO,IBEG
(1278)      IF (ISLO) 1,2,3
(1279)      1      SLOW = 2 0**ISLO
(1280)      RLAX = 0.1**ISLO
(1281)      GO TO 5
(1282)      2      RLAX = 1.0
(1283)      3      SLOW = 1.0
(1284)      IF (ISLO.EQ 0) GO TO 5
(1285)      RLAX = 10.0**ISLO
(1286)      5      LINE=0
(1287)      NT1 = NTORS+1
(1288)      NT2 = 2*NTORS
(1289)      NTB = NTORS+NBEND
(1290)      N2 = 2*NBEND
(1291)      N3 = N2+1
(1292)      NTB8 = NTORS+N2
(1293)      N22 = 2*N2
(1294)      N21 = N22-1

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(1295)      N23 = N22+1
(1296)      N24 = 2*NTBB
(1297)      DO 400 JASE=1,KASE
(1298)      DO 6 I=1,N2
(1299)      PLX(I) = 0.0
(1300)      PLX(N2+1) = 0.0
(1301)      DO 6 J=1,4
(1302)      FLX(J,I) = 0.0
(1303)  6    CONTINUE
(1304)      REWIND KSAVE
(1305)      REWIND KEEP
(1306)      READ (10) IDENT,NTITLE,NSPD,LBRG,LNODE,KRUN,LRUN
(1307)      IF(NBEND.GT.0) GO TO 2005
(1308)      IRUN=0
(1309)      GO TO 2017
(1310)  2005 IF(IRUN.GT.2) GO TO 2016
(1311)      IF(IRUN.EQ.0.OR.LRUN.EQ.1) GO TO 2017
(1312)  2010 WRITE(KW,2015) LRUN,IRUN
(1313)  2015 FORMAT (/19H PARAMETERS (LRUN =,15,7H IRUN =,15,19H) ARE INCOMPAT
(1314)      +IBLE.)
(1315)      CALL EXIT
(1316)  2016 IF(LRUN.EQ.1) GO TO 2010
(1317)  2017 CONTINUE
(1318)      IF (IRUN.NE.4) ITYPE = 0
(1319)      CALL RUNCON(KW,IRUN,ITYPE,IDENT,NTITLE)
(1320)      DO 399 KSPD=1,NSPD
(1321)      IF (NTORS.EQ.0) GO TO 120
(1322)      READ (10) (KEX(I),I=1,NTORS)
(1323)      IF (KSPD.GT.1) GO TO 120
(1324)      WRITE (KW,100)
(1325)  100   FORMAT (/30H TORSIONAL EXCITATION STATIONS)
(1326)      WRITE (KW,110) (KEX(I),I=1,NTORS)
(1327)  110   FORMAT(16I5)
(1328)  120   IF (NBEND.EQ.0) GO TO 140
(1329)      READ (10) (KEX(I),I=NT1,NTB)
(1330)      IF(LBRG.EQ.0) GO TO 125
(1331)      READ (10) (KBG(IBR),(BRGST(IBR,JBRG)),JBRG=1,2),IBR=1,LBRG
(1332)  125   CONTINUE
(1333)      IF (KSPD.GT.1) GO TO 140
(1334)      WRITE(KW,130)
(1335)  130   FORMAT (/28H BENDING EXCITATION STATIONS)
(1336)      WRITE(KW,110) (KEX(I),I=NT1,NTB)
(1337)  140   READ (10) IFRE
(1338)      DO 390 JFRE=1,IFRE
(1339)      IF(LRUN.EQ.1) GO TO 3901
(1340)      REWIND KSAVE
(1341)      REWIND KEEP
(1342)  3901  READ (10) NFREQ
(1343)      DO 380 KJ=1,NFREQ
(1344)      IF (NTORS.EQ.0) GO TO 265
(1345)      READ (10) FREQ(KJ)
(1346)      OMG=6.283185*FREQ(KJ)
(1347)      IONE = 1
(1348)      READ (10) (SHAPE(IPRINT,IONE),IPRINT=1,LNODE)

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(1349)      DO 150 I=1,NTORS
(1350)      READ (10) KU,(X(J,I),J=1,NTORS)
(1351) 150   CONTINUE
(1352)      IF(IDIAG.NE.2) GO TO 175
(1353)      WRITE (KW,170) IDENT,NTITLE
(1354) 170   FORMAT (1H1,20A4)
(1355)      WRITE (KW,160)
(1356) 160   FORMAT(26H TORSIONAL MOBILITY MATRIX/1H )
(1357) 175   DO 180 I=1,NTORS
(1358)      IRLAB(I) = I
(1359)      ICLAB(I) = I
(1360)      DO 180 J=1,NTORS
(1361)      J2 = 2*J
(1362)      J1 = J2-1
(1363)      XIN(I,J1) = X(I,J)
(1364)      XIN(I,J2) = 0.0
(1365)      XLX(I,J1) = X(I,J)
(1366) 180   XLX(I,J2) = 0.0
(1367)      IF(IDIAG.NE.2) GO TO 185
(1368)      DO 181 I=1,NTORS
(1369)      DO 181 J=1,NT2
(1370)      TABLX(I,J) = XLX(I,J)
(1371) 181   CONTINUE
(1372)      CALL MOUTC (TABLX,NTORS,NTORS,M60,JR,JC,IRLAB,ICLAB,LINE,KW)
(1373) 185   IF (KU.NE.2) GO TO 210
(1374)      WRITE (KW,190) FREQ(KJ)
(1375) 190   FORMAT (/1PE12.4,30H HZ IS A TORSIONAL RESONANT FREQUENCY /
(1376)      +37H EXECUTION HALTED, SEE USER'S MANUAL./1H1)
(1377)      CALL EXIT
(1378) 210   CALL INVC (NTORS,IERR)
(1379)      IF (IERR.NE.0) GO TO 4010
(1380)      DO 215 I=1,NTORS
(1381)      DO 215 J=1,NT2
(1382)      ZLX(I,J) = XOU(I,J)
(1383) 215   CONTINUE
(1384)      IF(IDIAG.NE.2) GO TO 240
(1385)      WRITE (KW,230)
(1386) 230   FORMAT (////27H TORSIONAL IMPEDANCE MATRIX/1H )
(1387)      DO 231 I=1,NTORS
(1388)      DO 231 J=1,NT2
(1389)      TABLX(I,J) = ZLX(I,J)
(1390) 231   CONTINUE
(1391)      CALL MOUTC (TABLX,NTORS,NTORS,M60,JR,JC,IRLAB,ICLAB,LINE,KW)
(1392) 240   IF (NBEND.EQ.0) GO TO 360
(1393)      DO 260 I=1,NTORS
(1394)      DO 260 J=1,NT2
(1395)      YLX(I,J) = ZLX(I,J)
(1396) 260   CONTINUE
(1397) 265   IF (NBEND.EQ.0) GO TO 360
(1398)      READ (10) FREQ(KJ),SPD
(1399)      UMG=6 283185*FREQ(KJ)
(1400)      SRPM = 60.0*SPD
(1401)      READ (10) (ENDET(IDET),IDET=1,2), (POSIT(IPRINT),(SHAPE(IPRINT
(1402)      + ISHAPE),ISHAPE=2,3),IPRINT=1,LNODE)

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(1403)      DO 280 I=1,NBEND
(1404)      READ (10) JORB,M8(I),K8(I)
(1405)      READ (10) (X(J,I),J=1,N2)
(1406) 280   CONTINUE
(1407)      IF(10IAG.NE.2) GO TO 295
(1408)      WRITE (KW,170) IDENT,HTITLE
(1409)      WRITE (KW,270) FREQ(KJ),SPD
(1410) 270   FORMAT(/10H FREQ      = ,1PE12.4,3H HZ/10H RPS      = ,E12.4,3H HZ)
(1411)      WRITE (KW,290)
(1412) 290   FORMAT(24HOBENDING MOBILITY MATRIX)
(1413) 295   NM1=NBEND-1
(1414)      DO 300 I=1,NM1
(1415)      IRLAB(I)=I
(1416)      ICLAB(I)=I
(1417)      L = NBEND+I
(1418)      IRLAB(L)=L
(1419)      ICLAB(L)=L
(1420)      I2 = 2*I
(1421)      I1 = I2-1
(1422)      XLX(I,I1) = X(I,I)
(1423)      XLX(I,I2) = 0.0
(1424)      XLX(L,I1) = 0.0
(1425)      XLX(L,I2) = X(L,I)
(1426)      L2 = 2*L
(1427)      L1 = L2-1
(1428)      XLX(I,L1) = -XLX(L,I1)
(1429)      XLX(I,L2) = -XLX(L,I2)
(1430)      XLX(L,L1) = XLX(I,I1)
(1431)      XLX(L,L2) = XLX(I,I2)
(1432)      IPLUS=I+1
(1433)      DO 300 J=IPLUS,NBEND
(1434)      J2 = 2*J
(1435)      J1 = J2-1
(1436)      X(J,I)=0.5*(X(J,I)+X(I,J))
(1437)      XLX(J,I1) = X(J,I)
(1438)      XLX(J,I2) = 0.0
(1439)      XLX(I,J1) = XLX(J,I1)
(1440)      XLX(I,J2) = XLX(J,I2)
(1441)      M = NBEND+J
(1442)      X(M,I)=0.5*(X(M,I)+X(L,J))
(1443)      XLX(M,I1) = 0.0
(1444)      XLX(M,I2) = X(M,I)
(1445)      XLX(L,J1)=XLX(M,I1)
(1446)      XLX(L,J2)=XLX(M,I2)
(1447)      XLX(J,L1)=-XLX(M,I1)
(1448)      XLX(J,L2)=-XLX(M,I2)
(1449)      M2 = 2*M
(1450)      M1 = M2-1
(1451)      XLX(I,M1)=XLX(J,L1)
(1452)      XLX(I,M2)=XLX(J,L2)
(1453)      XLX(L,M1) = XLX(I,J1)
(1454)      XLX(L,M2) = XLX(I,J2)
(1455)      XLX(M,L1) = XLX(J,I1)
(1456) 300   XLX(M,L2) = XLX(J,I2)

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(1457)      IRLAB(NBEND) = NBEND
(1458)      ICLAB(NBEND) = NBEND
(1459)      IRLAB(N2)=N2
(1460)      ICLAB(N2)=N2
(1461)      XLX(NBEND,N2-1) = X(NBEND,NBEND)
(1462)      XLX(NBEND,N2) = 0.0
(1463)      XLX(N2,N2-1) = 0.0
(1464)      XLX(N2,N2) = X(N2,NBEND)
(1465)      XLX(NBEND,N21) = -XLX(N2,N2-1)
(1466)      XLX(NBEND,N22) = -XLX(N2,N2)
(1467)      XLX(N2,N21) = XLX(NBEND,N2-1)
(1468)      XLX(N2,N22) = XLX(NBEND,N2)
(1469)      DO 302 I=1,N2
(1470)      DO 302 J=1,N22
(1471) 302   XIN(I,J) = XLX(I,J)
(1472)      IF(IDIAG.NE.2) GO TO 305
(1473)      DO 301 I=1,N2
(1474)      DO 301 J=1,N22
(1475) 301   TABLX(I,J) = XLX(I,J)
(1476)      CALL MOUTC (TABLX,N2,N2,M60,JR,JC,IRLAB,ICLAB,LINE,KW)
(1477) 305   IF (JORB.EQ.0) GO TO 320
(1478)      WRITE (KW,310) FREQ(KJ)
(1479) 310   FORMAT (1H1,1PE12.4,36H HZ IS A BENDING RESONANT FREQUENCY /
(1480)      +37H EXECUTION HALTED, SEE USER'S MANUAL./1H1)
(1481)      CALL EXIT
(1482) 320   CALL INVC (N2,IERR)
(1483)      IF (IERR.NE.0) GO TO 4010
(1484)      DO 321 I=1,N2
(1485)      DO 321 J=1,N22
(1486) 321   ZLX(I,J) = XOU(I,J)
(1487)      IF(NTORS.EQ.0) GO TO 360
(1488)      DO 331 I=1,N2
(1489)      DO 331 J=N23,N24
(1490)      ZLX(I,J) = 0.0
(1491) 331   CONTINUE
(1492)      DO 333 I=N3,NTBB
(1493)      IRLAB(I) = I
(1494)      ICLAB(I) = I
(1495)      DO 332 J=1,N22
(1496)      ZLX(I,J) = 0.0
(1497) 332   CONTINUE
(1498)      L = I-N22
(1499)      DO 333 J=N23,N24
(1500)      K = J-N22
(1501)      ZLX(I,J) = YLX(L,K)
(1502) 333   CONTINUE
(1503)      IF(IDIAG.NE.2) GO TO 360
(1504)      WRITE (KW,340)
(1505) 340   FORMAT (25H1BENDING IMPEDANCE MATRIX/1H )
(1506)      DO 334 I=1,N2
(1507)      DO 334 J=1,N22
(1508)      TABLX(I,J) = ZLX(I,J)
(1509) 334   CONTINUE
(1510)      CALL MOUTC (TABLX,N2,N2,M60,JR,JC,IRLAB,ICLAB,LINE,KW)

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(1511) 360 IF (IDIAG.NE.2) GO TO 3702
(1512) WRITE (KW,370) IDENT,NTITLE,SRPM,FREQ(KJ),NTBB
(1513) 370 FORMAT (43H1UNMODIFIED IMPEDANCE MATRIX RECORD SUMMARY/
(1514) +10H0IDENT = ,4A4/10H NTITLE = ,16A4/10H RPM = ,1PE12 4,
(1515) +3H H2/10H FREQ = ,E12.4,3H H2/10H RANK = ,13/1H )
(1516) DO 3701 I=1,NTBB
(1517) DO 3701 J=1,N24
(1518) TABIX(I,J) = ZLX(I,J)
(1519) 3701 CONTINUE
(1520) CALL MOUTC (TABLX,NTBB,NTBB,M60,JR,JC,IRLAB,ICLAB,LINE,KW)
(1521) 3702 IF (IRUN.EQ.0) GO TO 780
(1522) FSQ=FREQ(KJ)**2
(1523) IF (IRUN.GT.2) GO TO 42
(1524) C SYNCHRONISM CHECK
(1525) CHECK=FREQ(KJ)-SPD
(1526) CHECK=CHECK*CHECK/(FSQ+SPD*SPD)
(1527) IF (CHECK.LE.1.0E-08) GO TO 41
(1528) WRITE (KW,2000)
(1529) 2000 FORMAT (/60H SPEED-FREQUENCY DATA ARE FOUND INCONSISTENT IN SYNCHR
(1530) +25H CHECK. EXECUTION HALTED )
(1531) CALL EXIT
(1532) 41 INDEX = KSPD
(1533) SPEED(INDEX) = SPD
(1534) IF (IRUN.EQ.2) CENT = 0.0063856*FSQ
(1535) GO TO 43
(1536) 42 INDEX = KJ
(1537) C IMPEDANCE REVISION
(1538) 43 IF (LBRG.GT.0.OR IRUN.LT.2.OR IRUN.EQ.3) GO TO 441
(1539) WRITE(KW,4224)
(1540) 4224 FORMAT(73H COMPLEX EIGENVALUE LOGIC BEING USED UNNECESSARILY FOR A
(1541) +N UNDAMPED ROTOR //)
(1542) 441 IF (LBRG.GT.0.OR LBRG.GT.0) GO TO 44
(1543) DO 600 I=1,N2
(1544) DO 600 J=1,N22
(1545) 600 XLX(I,J)=ZLX(I,J)
(1546) GO TO 500
(1547) 44 I=1
(1548) KRGZ=0
(1549) NTEMP=1
(1550) NBRG = 0
(1551) IREV=0
(1552) KOUNT = 1
(1553) KBOH = 1
(1554) ITIME = 1
(1555) KBRG = 0
(1556) IF (IDIAG.NE.3) GO TO 4490
(1557) WRITE (KW,170)
(1558) WRITE (KW,4410) LBRG
(1559) 4410 FORMAT (40H NUMBER OF BRGS ASSIGNED IN LEVEL 1 =,I5)
(1560) IF (LBRG.EQ.0) GO TO 4420
(1561) WRITE (KW,4411) (KRG(I),I=1,LBRG)
(1562) 4411 FORMAT (/24H BEARING STATION NUMBERS,4I15)
(1563) IONE = 1
(1564) WRITE (KW,4412) (BRGST(I,IONE),I=1,LBRG)

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(1565) 4412 FORMAT (25H RADIAL STIFFNESS (LB/IN),5X,1P4D15.6)
(1566)      ITWO = 2
(1567)      WRITE (KU,4413) (BRGST(IBR,ITWO),IBR=1,LBRG)
(1568) 4413 FORMAT (30H ANGULAR STIFFNESS (IN-LB/RAD),1P4D15.6)
(1569) 4420 IF (IDRG.EQ.0) IPRI = -1
(1570) 4490 GO TO (46,47,45 47,45), IRUN
(1571) 45      IF (KJ.EQ.1) GO TO 47
(1572)      IF (IPRI) 379,48,48
(1573) 46      IF (KSPD.EQ.1) GO TO 47
(1574)      IF (IPRI) 379,48,48
(1575) 47      IF (IPRI.EQ.-1) GO TO 379
(1576)      WRITE (KU,170)
(1577) 48      WRITE (KU,610) SRPH, FREQ(KJ)
(1578) 610      FORMAT (/21H LEVEL 2 BEARING DATA/19H ROTATIONAL SPEED =,1PE11.4,4
(1579)      +H RPH,6X,11HFREQUENCY =,E11.4,3H HZ//8H BEARING,2X,4(1H*),6H TYPE
(1580)      +,4(1H*),2X,8(1H*),3H XX,2(1X,8(1H*),1X),2HXY,2(1X,8(1H*),1X),2HYX,
(1581)      +2(1X,8(1H*),1X),3HYY,8(1H*)/25H NO. STN RADIAL ANGULAR,4(5X,1HK
(1582)      +,10X,1HB,5X))
(1583) 379      IF (IDRG.EQ.0) GO TO 378
(1584) C READ BEARING DATA CONTROLS
(1585) 377      READ(KR,110) LO,NBRG,KBRG,IREV
(1586) 378      NBO=NTEMP
(1587)      DO 376 J=NRO,NBEND
(1588)      J02 = 2*J
(1589)      J01 = J02-1
(1590) C MATCH STATION NUMBER AND ACTION TYPE
(1591)      DO 401 IZ=1,2
(1592)      DO 401 JZ=1,2
(1593) 401      BRGLX(IZ,JZ) = 0.0
(1594)      NBRG = N0(J)
(1595)      LBG = K0(J)
(1596)      J1 = J+1
(1597)      JTYPE=LBG-2
(1598)      IF (KOUNT.GT.LBRG) GO TO 410
(1599)      K0GZ=K0G(KOUNT)
(1600)      IF (NBRG.NE.K0GZ) GO TO 410
(1601)      IF (JTYPE.LE.2) GO TO 406
(1602)      IF (JTYPE=5) 404,403,402
(1603) 402      JTYPE=JTYPE-1
(1604) 403      JTYPE=JTYPE-3
(1605)      IF (ITIME.EQ.2) GO TO 405
(1606)      ITIME=2
(1607)      JTYPE=JTYPE-1
(1608)      GO TO 406
(1609) 404      JTYPE=JTYPE-2
(1610)      GO TO 406
(1611) 405      ITIME=1
(1612) 406      DO 407 IZ=1,2
(1613)      BRGLX(IZ,IZ) = BRGST(KOUNT,JTYPE)
(1614)      DO 407 JZ=1,2
(1615)      JZ2 = 2*JZ
(1616)      JZ1 = JZ2-1
(1617)      TLX(IZ,JZ1) = 0.0
(1618) 407      TLX(IZ,JZ2) = 0.0

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(1619)      IF (JTYPE.EQ.2.OR.LBG.LT.6) KOUNT=KOUNT+1
(1620) 410   IF (NBRG.NE.NBRG) GO TO 375
(1621)      IF (IREV.EQ.0) GO TO 411
(1622)      IF (KBRG-1) 371,372,374
(1623) C ERROR MESSAGE FOR (NBRG,KBRG)
(1624) 371   WRITE (KW,10) I
(1625) 10    FORMAT (1H1,7(1H*),32H INPUT DATA IS FAULTY FOR BRG NO,13,7H. CHEC
(1626)      +34HK NBRG AND KBRG AGAINST N8 AND K8.,7(1H*))
(1627)      GO TO 400
(1628) 372   IF (LBG.LT.3.OR.LBG.EQ.4.OR.LBG.EQ.6) GO TO 371
(1629) C READ BEARING DATA
(1630) 373   READ(KR,2020) (((STIF(IONE,ITWO,I),DAMP(IONE,ITWO,I))),ITWO
(1631)      + =1,2),IONE=1,2)
(1632) 411   NTEMP = J1
(1633) 2020  FORMAT(8010.4)
(1634)      IF (IDIAG.NE.3) GO TO 375
(1635)      IF (KBRG.EQ.2) GO TO 4802
(1636)      WRITE (KW,4801) LO,NBRG,(((STIF(IONE,ITWO,I),DAMP(IONE,ITWO,I))),
(1637)      +ITWO=1,2),IONE=1,2)
(1638) 4801  FORMAT (13,I4,5X,1H*,12X,1P8D11.4)
(1639)      GO TO 4804
(1640) 4802  WRITE (KW,4803) LO,NBRG,(((STIF(IONE,ITWO,I),DAMP(IONE,ITWO,I))),
(1641)      +ITWO=1,2),IONE=1,2)
(1642) 4803  FORMAT (13,I4,13X,1H*,4X,1P8D11.4)
(1643) 4804  IPRI = -1
(1644)      GO TO 375
(1645) 374   IF (LBG.LT.4.OR.LBG.EQ.5) GO TO 371
(1646)      GO TO 373
(1647) 375   DO 369 K1=1,2
(1648)      L = NBEND*(K1-1)+J
(1649)      DO 369 K=1,NBEND
(1650)      DO 369 K2=1,2
(1651)      M = NBEND*(K2-1)+K
(1652)      M2 = 2*M
(1653)      M1 = M2-1
(1654)      XLX(L,M1) = ZLX(L,M1)
(1655)      XLX(L,M2) = ZLX(L,M2)
(1656)      IF(NTEMP.NE.J1 OR K.NE.J) GO TO 369
(1657)      K22 = 2*K2
(1658)      K21 = K22-1
(1659)      TLX(K1,K21) = STIF(K1,K2,I)-BRGLX(K1,K2)
(1660)      TLX(K1,K22) = OMG*DAMP(K1,K2,I)
(1661)      XLX(L,M1)=XLX(L,M1)+TLX(K1,K21)
(1662)      XLX(L,M2)=XLX(L,M2)+TLX(K1,K22)
(1663) 369   CONTINUE
(1664)      IF (NTEMP.NE.J1.AND.NBRG.NE.KBGZ) GO TO 376
(1665)      IF (IPRI.NE.-1)
(1666)      +CALL BRGTAB (KW,I,KBOTH,NBRG,KBRG,JTYPE,KBGZ,TLX,BRGLX,OMG)
(1667)      KBOTH=KBOTH+1
(1668)      IF(NTEMP.NE.J1 OR I.EQ.IBRG) GO TO 376
(1669)      I = I+1
(1670)      GO TO 377
(1671) 376   CONTINUE
(1672) 500   CONTINUE

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(1673)      CALL ISTRP(ISO,IBRG,STIF,DAMP,IRUN)
(1674)      IF(IBRG.EQ.0.OR.IDIAG.NE.2) GO TO 1000
(1675)      WRITE(KW,501) SPD,FREQ(KJ)
(1676)  501  FORMAT(50H1CARTESIAN IMPEDANCE MATRIX AFTER BEARING REVISION/20H
(1677)      +ROTATIONAL SPEED =,1PE11.4,3H HZ,7X,11HFREQUENCY =,E11.4,3H HZ//)
(1678)      DO 502 I=1,NTBB
(1679)      DO 502 J=1,N24
(1680)      TABLK(I,J) = XLX(I,J)
(1681)  502  CONTINUE
(1682)      CALL MOUTC (TABLK,NTBB,NTBB,M60,JR,JC,IRLAB,ICLAB,LINE,KW)
(1683)  C IMPEDANCE MATRIX TRANSFORMED TO ROTATING COORDINATES
(1684)  C UNDER BOTH ITYPE=1 AND 2
(1685)  1000 CALL ROTATE(NBEND)
(1686)      WRITE (KSAVE) SPD,FREQ(KJ),((YLX(I,J),J=1,N22),I=1,N2)
(1687)      IF(IDIAG.NE.2) GO TO 1001
(1688)      WRITE (KW,1510)
(1689)  1510 FORMAT(41H1IMPEDANCE MATRIX IN ROTATING COORDINATES//)
(1690)      DO 503 I=1,NTBB
(1691)      DO 503 J=1,N24
(1692)      TABLK(I,J) = YLX(I,J)
(1693)  503  CONTINUE
(1694)      CALL MOUTC (TABLK,NTBB,NTBB,M60,JR,JC,IRLAB,ICLAB,LINE,KW)
(1695)  1001 IF(IRUN.EQ.5) GO TO 380
(1696)      IF (IRUN.EQ.2.OR.IRUN.EQ.4) GO TO 71
(1697)      CALL IGRL(NBEND,INDEX,ISO,DETER,IWARN)
(1698)      GO TO 380
(1699)  C RESPONSE ORBITS
(1700)  71  DO 702 I=1,N2
(1701)      DO 702 J=1,N22
(1702)      XIN(I,J) = YLX(I,J)
(1703)  702  CONTINUE
(1704)      CALL INVC (N2,IERR)
(1705)  C NEED IERR CHECK HERE!
(1706)      DO 703 I=1,N2
(1707)      DO 703 J=1,N22
(1708)      XLX(I,J) = XOU(I,J)
(1709)  703  CONTINUE
(1710)  C READ EXCITATION CONTROLS
(1711)      IF (IRUN.EQ.0) GO TO 380
(1712)      READ (KR,110) IFORCE,IFDATA
(1713)      IF (IFDATA.EQ.0) GO TO 39
(1714)      READ (KR,110) (NFORCE(I),I=1,IFORCE)
(1715)      READ (KR,110) (KFORCE(I),I=1,IFORCE)
(1716)  39  NTFO=1
(1717)      NF = 0
(1718)      I = 1
(1719)      IF (IDIAG.NE.3) GO TO 72
(1720)      WRITE(KW,3907)
(1721)  3907 FORMAT(1X,27HEXCITATION INPUT DATA CHECK,/,1X,15HIFORCE, IFDATA /)
(1722)      WRITE (KW,110) IFORCE,IFDATA
(1723)      WRITE(KW,3902)
(1724)  3902 FORMAT(1X,6HMFORCE/)
(1725)      WRITE (KW,110) (NFORCE(IPRINT),IPRINT=1,IFORCE)
(1726)      WRITE(KW,3903)

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(1727) 3903  FORMAT(1X,6HKFORCE/)
(1728)      WRITE (KW,110) (KFORCE(IPRINT),IPRINT=1,IFORCE)
(1729) 72    NF = NFORCE(I)
(1730)      KF = KFORCE(I)
(1731) C     SEQUENCE THROUGH HALF-RANK
(1732)      NFO=NTFO
(1733)      DO 80 J=NFO,NBEND
(1734)      J02 = 2*J
(1735)      J01 = J02-1
(1736) C     IDENTIFY STATION NUMBER AND ACTION TYPE
(1737)      MF = M8(J)
(1738)      LF = K8(J)
(1739)      J1 = J+1
(1740) C     MATCH STATION NUMBERS
(1741)      IF (MF.NE.NF) GO TO 77
(1742) C     CHECK COMPATIBILITY
(1743)      IF (KF-1) 73,74,76
(1744) C     ERROR MESSAGE FOR (NFORCE,KFORCE)
(1745) 73    WRITE (KW,11) I
(1746) 11    FORMAT (1H1,3(1H*),34H INPUT DATA IS FAULTY FOR ENTRY NO,13,
(1747)      +27H 0 EITHER NFORCE OR KFORCE.,3(1H*))
(1748)      GO TO 400
(1749) 74    IF (LF.LT.3.OR.LF.EQ.4.OR.LF.EQ.6) GO TO 73
(1750) 75    NTFO=J1
(1751)      IF (IFDATA.EQ.0) GO TO 78
(1752) C     READ EXCITATION DATA
(1753)      READ (KR,2020) (FLX(IONE,I),IONE = 1,4)
(1754)      IF (IRUN.NE.2) GO TO 78
(1755)      FLX(3,I) = 0.0
(1756)      FLX(4,I) = 0.0
(1757) 78    DO 79 K1=1,2
(1758)      L = NBEND*(K1-1)+J
(1759)      K12 = 2*K1
(1760)      K11 = K12-1
(1761)      L2 = 2*L
(1762)      L1 = L2-1
(1763)      PLX(L1) = FLX(K11,I)
(1764)      PLX(L2) = FLX(K12,I)
(1765)      IF (IRUN.NE.2) GO TO 79
(1766)      PLX(L1) = CENT*PLX(L1)
(1767)      PLX(L2) = CENT*PLX(L2)
(1768) 79    CONTINUE
(1769)      IF (I.EQ.IFORCE) GO TO 83
(1770)      I = I+1
(1771)      GO TO 72
(1772) 76    IF (LF.LT.4.OR.LF.EQ.5) GO TO 73
(1773)      GO TO 75
(1774) 77    PLX(J01) = 0.0
(1775)      PLX(J02) = 0.0
(1776)      PLX(N2+J01) = 0.0
(1777)      PLX(N2+J02) = 0.0
(1778) 80    CONTINUE
(1779) 83    JF1=J02+1
(1780)      DO 82 J=JF1,N2

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(1781)          L=N2+J
(1782)          PLX(J)=0.0
(1783)  82      PLX(L)=0.0
(1784)          IF(IPRI.NE.-1) CALL XCITAB(KW,ITYPE,NBEND,M8,K8,PLX)
(1785)          WRITE(KSAVE)(PLX(I),I=1,N22)
(1786)  C      COMPUTE RESPONSE VECTOR
(1787)          IF(ITYPE.EQ.0) GO TO 832
(1788)  C      TRANSFORM FORCES FROM CARTESIAN TO ROTATING COORDINATES
(1789)          DO 831 IK=1,NBEND
(1790)              IK2 = 2*IK
(1791)              IK1 = IK2-1
(1792)              LK1 = N2+IK1
(1793)              LK2 = N2+IK2
(1794)              WLX(IK1) = 0.5*(PLX(IK1)-PLX(LK2))
(1795)              WLX(IK2) = 0.5*(PLX(IK2)+PLX(LK1))
(1796)              WLX(LK1) = 0.5*(PLX(IK1)+PLX(LK2))
(1797)              WLX(LK2) = 0.5*(PLX(IK2)-PLX(LK1))
(1798)              PLX(IK1) = WLX(IK1)
(1799)              PLX(IK2) = WLX(IK2)
(1800)              PLX(LK1) = WLX(LK1)
(1801)              PLX(LK2) = WLX(LK2)
(1802)  831      CONTINUE
(1803)  832      DO 84 I=1,N2
(1804)              I2 = 2*I
(1805)              I1 = I2-1
(1806)              WLX(I1) = 0.0
(1807)              WLX(I2) = 0.0
(1808)              DO 84 J=1,N2
(1809)                  J2 = 2*J
(1810)                  J1 = J2-1
(1811)                  WLX(I1) = XLX(I,J1)*PLX(J1)-XLX(I,J2)*PLX(J2)+WLX(I1)
(1812)                  WLX(I2) = XLX(I,J1)*PLX(J2)+XLX(I,J2)*PLX(J1)+WLX(I2)
(1813)  84      CONTINUE
(1814)          IF(IDIAG.NE.3) GO TO 1010
(1815)          WRITE(KW,3904)
(1816)  3904      FORMAT(1X,20HRESPONSE DIAGNOSTICS/1X,14HEXCITING FORCE/)
(1817)          WRITE(KW,1002)(PLX(IPRINT),IPRINT=1,N22)
(1818)          WRITE(KW,3905)
(1819)  3905      FORMAT(1X,30HRESPONSE DUE TO EXCITING FORCE/)
(1820)          WRITE(KW,1002)(WLX(IPRINT),IPRINT=1,N22)
(1821)  1002      FORMAT(10E12.3/10E12.3)
(1822)          DO 81 I=1,NTBB
(1823)              DO 81 J=1,N24
(1824)                  TABLX(I,J) = XLX(I,J)
(1825)  81      CONTINUE
(1826)          CALL MOUTC(TABLX,NTBB,NTBB,M60,JR,JC,IRLAB,ICLAB,LINE,KW)
(1827)  C      COMPUTE ORBIT PARAMETERS
(1828)  1010      DO 85 I=1,NBEND
(1829)              I2 = 2*I
(1830)              I1 = I2-1
(1831)              L = NBEND+I
(1832)              L2 = 2*L
(1833)              L1 = L2-1
(1834)  85      CALL ORBIT(ITYPE,BIG(I),SMALL(I),SLANT(I),PHASE(I),

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(1835)      +          WLX(I1),WLX(I2),WLX(L1),WLX(L2))
(1836) C WRITE PART II OF SYDSYN OUTPUT
(1837)      IORB = 1
(1838)      CALL ORBTAB(KW,NBEND,M0,K0,SRPM,FREQ(KJ),BIG,SMALL,SLANT,
(1839)      +PHASE,POSIT,IORB)
(1840) 380 CONTINUE
(1841)      IF (NBEND.EQ.0) GO TO 400
(1842)      READ (10) (K9(I),I=1,NBEND)
(1843)      IF(IRUN-3) 390,386,385
(1844) 386 CONTINUE
(1845)      WRITE(KW,382) SRPM
(1846) 382 FORMAT (45H:UNDAMPED ASYNCHRONOUS STIFFNESS DETERMINANTS/
(1847)      +19H ROTATIONAL SPEED =,1PE11.4,4H RPM/)
(1848)      IF (ISO.EQ.1) GO TO 383
(1849)      WRITE (KW,387)
(1850) 387 FORMAT (/10H FREQUENCY,7X,6(1H*),14H DETERMINANTS ,7(1H*)/
(1851)      +7H (HZ),12X,7HCO -ROT,9X,7HCTR-ROT)
(1852)      GO TO 384
(1853) 383 WRITE (KW,388)
(1854) 388 FORMAT (/10H FREQUENCY,6X,11HDETERMINANT/7H (HZ),11X,7HCOUPLED)
(1855) 384 CALL ASNTAB(KW,NFREQ,IWARN,FREQ.DETER,ISO)
(1856) C INTERPOLATION FOR ASYNCHRONOUS RESONANCE
(1857)      CALL ENTER(KSAVE,KEEP,KW,NBEND,NFREQ,ISO,DETER,FREQ,SPEED,
(1858)      + RET,XINT,IRUN,IDIAG)
(1859)      GO TO 390
(1860) C STABILITY-MARGIN/DAMPED RESONANCE
(1861) 385 IF (IGEN.EQ.0) GO TO 390
(1862)      CALL KRAUTE(NFREQ,NBEND,KSAVE,KEEP,KW,ITYPE,ISO,FREQ,SPEED,IRUN,
(1863)      +TABLX,PLX,WLX,BIG,SMALL,SLANT,PHASE,IDIAG)
(1864) 390 CONTINUE
(1865) 399 CONTINUE
(1866)      IF (IRUN.LE.0) GO TO 400
(1867)      IF (IRUN-2) 391,394,400
(1868) 391 WRITE(KW,392)
(1869) 392 FORMAT(28H1CRITICAL SPEED DETERMINANTS//16H SPEED (RPM)
(1870)      +11HDETERMINANT)
(1871)      CALL SYNTAB(KW,NSPD,IWARN,SPEED,DETER,ISO)
(1872) C CRITICAL SPEED AND UNBALANCE RESPONSE INTERPOLATION
(1873)      CALL ENTER(KSAVE,KEEP,KW,NBEND,NSPD,ISO,DETER,SPEED,FREQ,
(1874)      + RET,XINT,IRUN,IDIAG)
(1875)      GO TO 400
(1876) C UNBALANCE RESPONSE AT RESONANCE
(1877) 394 IF (IGEN.EQ.0) GO TO 400
(1878)      KTYPE = 0
(1879)      CALL KRAUTE(NSPD,NBEND,KSAVE,KEEP,KW,KTYPE,ISO,SPEED,FREQ,IRUN,
(1880)      +TABLX,PLX,WLX,BIG,SMALL,SLANT,PHASE,IDIAG)
(1881) 400 CONTINUE
(1882) 4005 RETURN
(1883) 4010 WRITE (KW,4011)
(1884) 4011 FORMAT (50H1INVERSION OF A SINGULAR COMPLEX MATRIX ATTEMPTED!)
(1885)      GO TO 4005
(1886)      END

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(1887) SUBROUTINE SPLINE(NI, NP, RET, XINT, X, Y, Z, KW, IER)
(1888) C NI RUN CONTROL - <0 OBTAIN SPLINE COEFFICIENTS
(1889) C 0 LOOK FOR ROOTS
(1890) C 100 LOCATE WELL
(1891) C OTHERS NUMBER OF INTERPOLATION POINTS
(1892) C ON RETURN - NUMBER OF ROOTS FOUND
(1893) C NP NUMBER OF GIVEN DATA POINTS, MUST NOT EXCEED 11
(1894) C XINT X VALUES TO BE INTERPOLATED OR
(1895) C SLOPE AT ROOTS
(1896) C RET Y VALUES FROM INTERPOLATION OF GIVEN X'S
(1897) C X VALUES OF COMPUTED ROOTS
(1898) C ARRAY SIZE MUST BE AT LEAST 11 IN THE CALLING PROGRAM
(1899) C X X DATA VALUES
(1900) C Y Y DATA VALUES
(1901) C Z SPLINE COEFFICIENTS
(1902) C KW OUTPUT DEVICE NUMBER
(1903) C IER DIAGNOSTIC CONTROL
(1904) C 0 - NO PRINTOUT
(1905) C 1 - PRINT ONLY ANSWERS
(1906) C 2 - FULL DIAGNOSTIC PRINTOUT
(1907) C ON RETURN - ERROR STATUS
(1908) C 0 - NO ERRORS
(1909) C 1 - VALUE FOR INTERPOLATION OUT OF BOUNDS
(1910) C 2 - ITERATION ERROR
(1911) C DCB'S MODIFICATIONS ADDED MAY 23, 1979 BY CHTP
(1912) C
(1913) C INTEGER O
(1914) C DIMENSION XINT(1), RET(1), X(1), Y(1), Z(3,1)
(1915) C DIMENSION D(2,2), D1(2,2), D9(2,2), E(2), E1(2), E9(2),
(1916) C +R1(20,2), R2(20)
(1917) C NPM = NP-1
(1918) C IF (NI.NE.100) GO TO 2000
(1919) 2000 IPR=IER
(1920) IER=0
(1921) I=0
(1922) D(1,1)=1.
(1923) D(1,2)=0.
(1924) D(2,1)=0.
(1925) D(2,2)=1.
(1926) E(1)=0.
(1927) E(2)=0.
(1928) D1(1,1)=-2.
(1929) D1(2,2)=-2.
(1930) E1(2)=1.
(1931) 111 I=I+1
(1932) IFLAG=1
(1933) GO TO 720
(1934) 120 DO 124 I1=1,2
(1935) DO 124 I2=1,2
(1936) D9(I1,I2)=0.
(1937) DO 124 I3=1,2
(1938) 124 D9(I1,I2)=D9(I1,I2) + D1(I1,I3)*D(I3,I2)
(1939) D(1,1)=D9(1,1)
(1940) D(1,2)=D9(1,2)

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(1941)      D(2,1)=D9(2,1)
(1942)      D(2,2)=D9(2,2)
(1943)      GO TO 710
(1944) 131   IF(I.LT.NP-1) GO TO 111
(1945)      Y1= -(1./D(2,1))*E(2)
(1946)      IF(NI=0) 300,300,140
(1947) 140   I2=0
(1948)      NWELL=0
(1949)      IF(NI.NE.100) GO TO 141
(1950)      I=1
(1951)      TANK=1.0E+5
(1952)      X1=0.0
(1953)      IFLAG=5
(1954)      E(1)=Y1
(1955)      E(2)=0.
(1956)      GO TO 730
(1957) 143   I2=0
(1958)      IF (I.EQ.NPM) GO TO 747
(1959)      GO TO 720
(1960) 145   I1=1
(1961)      B1=E(2)/Y3
(1962)      A1=2.*E(1)/Y3
(1963)      C1=B1*B1-A1
(1964)      IF(C1.LT.0.) GO TO 143
(1965)      C2=SQRT(C1)
(1966)      XQ=-A1+C2
(1967)      IF(XQ.LT.0.0) GO TO 143
(1968) 146   RET(1)=X(I)+XQ
(1969)      IF(RET(1).GE.X(I+1)) GO TO 147
(1970)      T9=E(2)+Y3*XQ
(1971)      IF(T9.LT.0.) GO TO 147
(1972)      NWELL=1
(1973)      NI=NWELL
(1974)      Y1=Y(I)+XQ*(E(1)+XQ*(0.5*E(2)+XQ*Y3/6.))
(1975)      IF(Y1=0.0) 147,147,50
(1976) 50    IF(Y1.GT.TANK.OR.RET(1).LT.X(1).OR.RET(1).GT.X(NP)) GO TO 147
(1977)      TANK=Y1
(1978)      X1=RET(1)
(1979)      GO TO 147
(1980) 747   IF(X1.LT.X(1).OR.X1.GT.X(NP)) GO TO 700
(1981)      RET(1)=X1
(1982)      Y1=TANK
(1983)      GO TO 700
(1984) 147   IF(I2.EQ.2) GO TO 143
(1985)      I2=2
(1986)      XQ=-B1-C2
(1987)      GO TO 146
(1988) 141   DO 270 INDEX=1,NI
(1989)      XS=XINT(INDEX)
(1990)      I=0
(1991)      IF(XS.GE.X(1).AND.XS.LE.X(NP))      GO TO 210
(1992)      IF (IPR.GT.0) WRITE (KW,200) X(1),X(NP),INDEX,XS
(1993) 200   FORMAT (/25H DATA PASSING ERROR. LOW= ,E16.8,12H      HIGH=
(1994)      +E16.9,8H      AT ,I2,9HX VALUE= ,E16.8)

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(1995)      IER=1
(1996)      GO TO 700
(1997) 210   I=I+1
(1998)      IF (I.EQ.NP) GO TO 220
(1999)      IF (XS.GE.X(I)) GO TO 210
(2000) 220   K=I-1
(2001)      I=0
(2002)      E(1)=Y1
(2003)      E(2)=0.
(2004) 230   I=I+1
(2005)      IFLAG=2
(2006)      IF (I.EQ.K) GO TO 260
(2007)      GO TO 720
(2008) 260   GO TO 730
(2009) 261   YS=Y(I)+(XS-X(I))*E(1)+0.5*(XS-X(I))**2*E(2)+
(2010)      +(1./6.)*(XS-X(I))**3*Y3
(2011)      RET(INDEX)=YS
(2012)      Z(1,I)=E(1)
(2013)      Z(2,I)= 0.5*E(2)
(2014)      Z(3,I)= Y3/6.
(2015)      IF (IPR.GT.0) WRITE (KW,264) INDEX,XS,YS
(2016) 264   FORMAT (5X,I3,3X,29HTHE INTERPOLATED VALUE AT X = ,E16.8,
(2017)      +4H IS ,E16.8)
(2018) 270   CONTINUE
(2019)      GO TO 700
(2020) C     ROOT FINDING
(2021) 300   I=0
(2022)      DO 3003 IC=1,11
(2023) 3003  RET(IC)=0.0
(2024)      RET(1)=0.0
(2025)      RET(2)=0.0
(2026)      RET(3)=0.0
(2027)      RET(4)=0.0
(2028)      R1(1,1)=X(1)
(2029)      R1(1,2)=Y(1)
(2030)      E(1)=Y1
(2031)      E(2)=0.
(2032)      J=1
(2033) 310   I=I+1
(2034)      IFLAG=3
(2035)      IF (I.LT.NP) GO TO 730
(2036)      IF (NI.LT.0) GO TO 700
(2037)      GO TO 470
(2038) 321   Z(1,I)=E(1)
(2039)      Z(2,I)=0.5*E(2)
(2040)      Z(3,I)=Y3/6
(2041)      IF (NI.LT.0) GO TO 720
(2042)      A=Y3/2
(2043)      B=E(2)-X(I)*Y3
(2044)      C=E(1)-X(I)*E(2)+0.5*X(I)**2*Y3
(2045)      IF (SQRT((A*X(I+1)**2)**2+(B*X(I+1)**2)/SQRT((A*X(I+1)**2)**2
(2046)      +(B*X(I+1)**2+C**2).LT.0.001) GO TO 720
(2047)      IF (ABS(A*X(I+1)**2/SQRT((A*X(I+1)**2)**2
(2048)      +(B*X(I+1)**2+C**2).GT.0.001) GO TO 360

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(2049)      Z2=-C/B
(2050)      GO TO 420
(2051) 360  ZZ=B**2-4.*A*C
(2052)      IF (ZZ.LT.0.) GO TO 720
(2053)      Z1=-B-SQRT(ZZ)
(2054)      Z2=-B+SQRT(ZZ)
(2055)      Z1=Z1/(2.*A)
(2056)      Z2=Z2/(2.*A)
(2057)      IF (Z1.LT.X(I).OR.Z1.GT.X(I+1)) GO TO 420
(2058)      XS=Z1
(2059)      YS=Y(I)+(XS-X(I))*E(1)+0.5*(XS-X(I))*2*E(2)+
(2060)      +(1./6.)*(XS-X(I))*3*Y3
(2061)      IF (R1(J,2)*YS.LE.0.0) GO TO 410
(2062)      IF (J.GT.1) GO TO 420
(2063)      J=0
(2064) 410  J=J+1
(2065)      R1(J,1)=Z1
(2066)      R1(J,2)=YS
(2067) 420  IF (Z2.LE.X(I).OR.Z2.GT.X(I+1)) GO TO 720
(2068)      XS=Z2
(2069)      YS=Y(I)+(XS-X(I))*E(1)+0.5*(XS-X(I))*2*E(2)+
(2070)      +(1./6.)*(XS-X(I))*3*Y3
(2071)      IF (R1(J,2)*YS.LE.0.0) GO TO 450
(2072)      IF (J.GT.1) GO TO 720
(2073)      J=0
(2074) 450  J=J+1
(2075)      R1(J,1)=Z2
(2076)      R1(J,2)=YS
(2077)      GO TO 720
(2078) 470  IF (R1(J,2)*Y(NP).GT.0.) GO TO 480
(2079)      J=J+1
(2080)      R1(J,1)=X(NP)
(2081)      R1(J,2)=Y(NP)
(2082) 480  IF (IPR.LT.2) GO TO 490
(2083)      DO 481 I1=1,J
(2084) 481  WRITE (KW,482) R1(I1,1),R1(I1,2)
(2085) 482  FORMAT (5X,E16.8,5X,E16.8)
(2086) 490  O=0
(2087)      IF (J.EQ.1) GO TO 532
(2088)      IUP=J-1
(2089)      DO 520 I=1,IUP
(2090)      IF (R1(I+1,1).NE.R1(I,1)) GO TO 510
(2091)      O=O+1
(2092)      GO TO 520
(2093) 510  R2(I-O)=R1(I+1,1)-R1(I+1,2)*(R1(I+1,1)-R1(I,1))/(R1(I+1,2)
(2094)      +R1(I,2))
(2095) 520  CONTINUE
(2096)      IF (IPR.LE.1) GO TO 532
(2097)      IUP=J-1-O
(2098)      DO 531 I1=1,IUP
(2099) 531  WRITE (KW,482) R2(I1)
(2100) 532  NI=J-O-1
(2101)      IF (NI.LE.0) GO TO 700
(2102)      DO 690 I7=1,NI

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(2103)      XS=R2(I7)
(2104)      OLDDX=1.0E-25
(2105) 540   I=0
(2106)      IF (XS.GE.X(1).AND.XS.LE.X(NP)) GO TO 570
(2107)      IF (IPR.GT.0) WRITE (KW,561) X(1),XS,X(NP)
(2108) 561   FORMAT (24H ITERATION ERROR X(1)= ,E16.8,4H XS ,E16.8,7H X(NP)
(2109)      +E16.8)
(2110)      IER=2
(2111)      GO TO 700
(2112) 570   I=I+1
(2113)      IF (I.EQ.NP) GO TO 580
(2114)      IF (XS.GE.X(I)) GO TO 570
(2115) 580   K=I-1
(2116)      I=0
(2117)      E(1)=Y1
(2118)      E(2)=0
(2119) 590   I=I+1
(2120)      IFLAG=4
(2121)      IF (I.NE.K) GO TO 720
(2122)      GO TO 730
(2123) 621   YS=Y(I)+(XS-X(I))*E(1)+0.5*(XS-X(I))*2*E(2)+
(2124)      +(1./6.)*(XS-X(I))*3*Y3
(2125)      S1=E(1)+(XS-X(I))*E(2)+0.5*(XS-X(I))*2*Y3
(2126)      S2=E(2)+(XS-X(I))*Y3
(2127)      IF (ABS(S1).LE.1.0E-15) GO TO 660
(2128)      X9=XS-YS/S1
(2129)      IF (IPR.GT.1) WRITE (KW,632) XS,X9,YS,S1
(2130) 632   FORMAT (4(5X,E16.8))
(2131)      CHECKX=0.001*ABS(OLDDX)
(2132)      IF (ABS(XS-X9).LE.CHECKX) GO TO 660
(2133) C     ADDITION (DCB)
(2134)      IF(X9.GE.R1(I7,1)) GOTO 633
(2135)      XS=R1(I7,1)
(2136)      GOTO 540
(2137) 633   IF(X9.LE.R1(I7+1,1)) GOTO 634
(2138)      XS=R1(I7+1,1)
(2139)      GOTO 540
(2140) C     END ADDITION (DCB)
(2141) 634   OLDDX=XS-X9
(2142)      Y9=YS+S1*(X9-XS)+(S2/2.)*(X9-XS)*2+(Y3/6.)*(X9-XS)*3
(2143)      XS=XS-YS*(X9-XS)/(Y9-YS)
(2144)      GO TO 540
(2145) 660   RET(I7)=XS
(2146)      XINT(I7)=S1
(2147)      IF (IPR.GT.0) WRITE (KW,680) I7,XS,S1
(2148) 680   FORMAT (5X,13H ROOT NUMBER ,12,4H AT ,E16.8,9H SLOPE = ,E16.8,
(2149) 690   CONTINUE
(2150) 700   CONTINUE
(2151)      RETURN
(2152) C     MAT E9=D1+E AND MAT E=E9+E1
(2153) 710   DO 714 I1=1,2
(2154)      E9(I1)=0.0
(2155)      DO 714 I2=1,2
(2156) 714   E9(I1)=E9(I1)+D1(I1,I2)*E(I2)

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(2157)      E(1)=E9(1)+E1(1)
(2158)      E(2)=E9(2)+E1(2)
(2159)      GO TO (131,230,310,590,720), IFLAG
(2160)      C      SUBROUTINE *2
(2161)      720      VAL=X(I+1)-X(I)
(2162)      D1(1,2)=-.5*VAL
(2163)      D1(2,1)=-6./VAL
(2164)      E1(1)=-D1(1,2)
(2165)      E1(2)=1.0
(2166)      DO 726 I1=1,2
(2167)      726      E1(I1)=E1(I1)*(6.*(Y(I+1)-Y(I))/VAL**2)
(2168)      GO TO (120,710,710,710,710), IFLAG
(2169)      C      SUBROUTINE *3
(2170)      728      I=I+1
(2171)      730      VAL=X(I+1)-X(I)
(2172)      Y3=(Y(I+1)-Y(I))-VAL*E(1)-0.5*VAL**2*E(2)
(2173)      Y3=6.*Y3/VAL**3
(2174)      GO TO (131,261,321,621,145), IFLAG
(2175)      END

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(2176) SUBROUTINE PINVC(ID,KW,N,NA,NB,IS,IROT,TABLX,JDIAG)
(2177) C   TABLX      INPUT COMPLEX MATRIX
(2178) C   REPLACED BY ITS INVERSE UPON RETURN
(2179) C   ID        0   CALCULATE DETERMINANT DLX ONLY
(2180) C               1   PERFORM INVERSION AND CALCULATE DETERMINANT
(2181) C
(2182) C           A0   B0                      A1   B1
(2183) C   TABLX =                      INV(TABLX) =
(2184) C           C0   D0                      C1   D1
(2185) C
(2186) COMMON/BMAT/XLX(60,120),YLY(60,120),ZLX(60,120),
(2187) +XHALF(20,40),YHALF(20,40),ZHALF(20,40),QHALF(20,40)
(2188) COMMON/BINV/XIN(60,122),XOU(60,122),DLX(2),IROW(61),ICOL(61)
(2189) DIMENSION TABLX(60,1)
(2190) DIMENSION SUMX(2)
(2191) IW=0
(2192) N2 = 2*N
(2193) M60=60
(2194) M20=20
(2195) JR=1
(2196) LINE=0
(2197) IF (JDIAG.NE.5) GO TO 105
(2198) DO 100 I=1,N2
(2199) IROW(I) = I
(2200) ICOL(I) = I
(2201) 100 CONTINUE
(2202) WRITE(KW,9876)
(2203) 9876 FORMAT(/17H SUBROUTINE PINVC/)
(2204) CALL MOUTC(TABLX,N2,N2,M60,JR,JR,IROW,ICOL,LINE,KW)
(2205) 105 DO 160 L= 1,2
(2206) IF (ID - 1) 110,130,190
(2207) 110 IF (IS .EQ. 1) GO TO 130
(2208) IF (IROT .NE. L) GO TO 160
(2209) 130 MB= (L-1)*N
(2210) MB2 = 2*MB
(2211) IB= (2-L)*N
(2212) IB2 = 2*IB
(2213) C   FOR      L = 1          2
(2214) C   SET UP      A0          D0
(2215) DO 140 I= 1,N
(2216) IO= I+MB
(2217) DO 140 J= 1,N2
(2218) JO= J+MB2
(2219) XIN(I,J)= TABLX(IO,JO)
(2220) 140 CONTINUE
(2221) C   FOR      L = 1          2
(2222) C   INVERT      A0          D0
(2223) IF(JDIAG.EQ.5) CALL MOUTC(XIN,N,N,M60,JR,JR,IROW,ICOL,LINE,KW)
(2224) CALL INVC(N,IERR)
(2225) DRE = DLX(1)
(2226) DIM = DLX(2)
(2227) IF (JDIAG.NE.5) GO TO 1405
(2228) DO 1402 I=1,N2
(2229) IROW(I) = I

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(2230)      ICOL(1) = I
(2231) 1402  CONTINUE
(2232)      CALL MOUTC(XOU,N,N,M60,JR,JR,IROW,ICOL,LINE,KW)
(2233)      WRITE(KW,1100)DLX(1),DLX(2)
(2234) 1100  FORMAT(13H DETERMINANT=,1PE13.6,1H,,1PE13.6)
(2235) C      FOR          L = 1          2
(2236) C      STORE          INV(A0)    INV(D0)
(2237) 1405  DO 1410 I=1,N
(2238)      DO 1410 J=1,N2
(2239)      YHALF(I,J) = XOU(I,J)
(2240) 1410  CONTINUE
(2241)      IF (IS.EQ.1) GO TO 145
(2242)      IF (IERR.NE.0) WRITE(KW,1000)
(2243) C      FOR          L = 1          2
(2244) C      STORE          A1          D1          FOR ISOTROPIC CASE
(2245)      DO 142 I=1,N
(2246)      IO=I+MB
(2247)      DO 142 J=1,N2
(2248)      JO=J+MB2
(2249) 142   TABLX(IO,JO)=YHALF(I,J)
(2250)      IF(JDIAG.EQ.5) CALL MOUTC(YHALF,N,N,M20,JR,JR,IROW,ICOL,LINE,KW)
(2251)      GO TO 160
(2252) C      FOR          L = 1          2
(2253) C      NULL TEST OF  DET(A0)    DET(D0)
(2254) 145   IF (IERR.EQ.0) GO TO 150
(2255)      IF (L.EQ.1) IW=1
(2256)      IF (L.EQ.1.OR.IW.EQ.0) GO TO 160
(2257)      WRITE (KW,1000)
(2258) 1000  FORMAT (1H1,45H ILL-CONDITIONED MATRIX ENCOUNTERED IN PINVC )
(2259)      CALL EXIT
(2260) C      FOR          L = 1          2
(2261) C      SET UP          CO,B0          B0,CO
(2262) 150   DO 170 I= 1,N
(2263)      IO= I+IB
(2264)      I1=I+MB
(2265)      DO 170 J=1,N2
(2266)      JO= J+IB2
(2267)      J1= J+MB2
(2268)      XHALF(I,J)=TABLX(IO,J1)
(2269) 170   ZHALF(I,J)=TABLX(I1,JO)
(2270)      IF (JDIAG.NE.5) GO TO 1710
(2271)      CALL MOUTC(XHALF,N,N,M20,JR,JR,IROW,ICOL,LINE,KW)
(2272)      CALL MOUTC(ZHALF,N,N,M20,JR,JR,IROW,ICOL,LINE,KW)
(2273) C      FOR          L = 1          2
(2274) C      CALC          CO*INV(A0)    B0*INV(D0)
(2275) 1710  DO 171 I=1,N
(2276)      DO 171 J=1,N
(2277)      J2 = 2*J
(2278)      J1 = J2-1
(2279)      SUMX(1) = 0.0
(2280)      SUMX(2) = 0.0
(2281)      DO 169 K=1,N
(2282)      K2 = 2*K
(2283)      K1 = K2-1

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(2284)      SUMX(1) = SUMX(1)+XHALF(I,K1)*YHALF(K,J1)-XHALF(I,K2)*YHALF(K,J2)
(2285)      SUMX(2) = SUMX(2)+XHALF(I,K1)*YHALF(K,J2)+XHALF(I,K2)*YHALF(K,J1)
(2286) 169   CONTINUE
(2287)      QHALF(I,J1) = SUMX(1)
(2288)      QHALF(I,J2) = SUMX(2)
(2289) 171   CONTINUE
(2290)      IF(JDIAG.EQ.5) CALL MOUTC(QHALF,N,N,M20,JR,JR,IROW,ICOL,LINE,KW)
(2291)  C    FOR      L = 1      2
(2292)  C    CALC      D1,C1      A1,B1
(2293)      DO 172 I=1,N
(2294)      IO=I+IB
(2295)      DO 172 J=1,N
(2296)      J2 = 2*J
(2297)      J1 = J2-1
(2298)      SUMX(1) = 0.0
(2299)      SUMX(2) = 0.0
(2300)      J02 = J2+IB2
(2301)      J01 = J02-1
(2302)      DO 169 K=1,N
(2303)      K2 = 2*K
(2304)      K1 = K2-1
(2305)      SUMX(1) = SUMX(1)+QHALF(I,K1)*ZHALF(K,J1)-QHALF(I,K2)*ZHALF(K,J2)
(2306)      SUMX(2) = SUMX(2)+QHALF(I,K1)*ZHALF(K,J2)+QHALF(I,K2)*ZHALF(K,J1)
(2307) 168   CONTINUE
(2308)      XIN(I,J1) = TABLX(IO,J01)-SUMX(1)
(2309)      XIN(I,J2) = TABLX(IO,J02)-SUMX(2)
(2310) 172   CONTINUE
(2311)      IF(JDIAG.EQ.5) CALL MOUTC(XIN,N,N,M60,JR,JR,IROW,ICOL,LINE,KW)
(2312)      CALL INVC(N,IERR)
(2313)      D1=DRE*DLX(1)-DIM*DLX(2)
(2314)      DIM=DRE*DLX(2)+DIM*DLX(1)
(2315)      DRE=D1
(2316)      IF (JDIAG.NE.5) GO TO 1720
(2317)      DO 1725 I=1,N2
(2318)      IROW(I) = I
(2319)      ICOL(I) = I
(2320) 1725   CONTINUE
(2321)      CALL MOUTC(XOU,N,N,M60,JR,JR,IROW,ICOL,LINE,KW)
(2322)      WRITE(KW,1100)DLX(1),DLX(2)
(2323) 1720   IF (ID.EQ.0) GO TO 190
(2324)      DO 173 I=1,N
(2325)      DO 173 J=1,N2
(2326)      ZHALF(I,J) = XOU(I,J)
(2327) 173   CONTINUE
(2328)      IF(JDIAG.EQ.5) CALL MOUTC(ZHALF,N,N,M20,JR,JR,IROW,ICOL,LINE,KW)
(2329)      DO 180 I= 1,N
(2330)      IO= I+IB
(2331)      II= I+MB
(2332)      DO 180 J= 1,N
(2333)      J2 = 2*J
(2334)      J1 = J2-1
(2335)      J02 = J2+IB2
(2336)      J01 = J02-1
(2337)      J12 = J2+MB2

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(2338)      J11 = J12-1
(2339)      TABLX(10,J01) = ZHALF(I,J1)
(2340)      TABLX(10,J02) = ZHALF(I,J2)
(2341)      XHALF(I,J1) = 0.0
(2342)      XHALF(I,J2) = 0.0
(2343)      DO 175 K= 1,N
(2344)      K2 = 2*K
(2345)      K1 = K2-1
(2346)      XHALF(I,J1) = XHALF(I,J1)-ZHALF(I,K1)*QHALF(K,J1)+ZHALF(I,K2)
(2347)      +                                *QHALF(K,J2)
(2348)      XHALF(I,J2) = XHALF(I,J2)-ZHALF(I,K1)*QHALF(K,J2)-ZHALF(I,K2)
(2349)      +                                *QHALF(K,J1)
(2350) 175  CONTINUE
(2351)      TABLX(10,J11) = XHALF(I,J1)
(2352)      TABLX(10,J12) = XHALF(I,J2)
(2353) 180  CONTINUE
(2354)  C    FOR          L = 1          2
(2355)  C    STORE          A1          D1
(2356)      IF(JDIAG.EQ.5) CALL MOUTC(XHALF,N,N,M20,JR,JR,IROW,ICOL,LINE,KW)
(2357)      DO 181 I=1,N
(2358)      I1=I+MB
(2359)      DO 181 J=1,N2
(2360)      J0=J+MB2
(2361) 181  QHALF(I,J)=TABLX(I1,J0)
(2362)      IF(JDIAG.EQ.5) CALL MOUTC(QHALF,N,N,M20,JR,JR,IROW,ICOL,LINE,KW)
(2363)      DO 182 I=1,N
(2364)      DO 182 J=1,N
(2365)      J2 = 2*J
(2366)      J1 = J2-1
(2367)      SUMX(1) = 0.0
(2368)      SUMX(2) = 0.0
(2369)      DO 183 K=1,N
(2370)      K2 = 2*K
(2371)      K1 = K2-1
(2372)      SUMX(1) = SUMX(1)+QHALF(I,K1)*XHALF(K,J1)-QHALF(I,K2)*XHALF(K,J2)
(2373)      SUMX(2) = SUMX(2)+QHALF(I,K1)*XHALF(K,J2)+QHALF(I,K2)*XHALF(K,J1)
(2374) 183  CONTINUE
(2375)      ZHALF(I,J1) = -SUMX(1)
(2376)      ZHALF(I,J2) = -SUMX(2)
(2377)      IF (I.NE.J) GO TO 182
(2378)      ZHALF(I,J1) = 1.0-SUMX(1)
(2379) 182  CONTINUE
(2380)      IF(JDIAG.EQ.5) CALL MOUTC(ZHALF,N,N,M20,JR,JR,IROW,ICOL,LINE,KW)
(2381)  C    FOR          L = 1          2
(2382)  C    CALC          INV(A0)    INV(D0)
(2383)      DO 184 I=1,N
(2384)      I0=I+MB
(2385)      DO 184 J=1,N
(2386)      J2 = 2*J
(2387)      J1 = J2-1
(2388)      J02 = J2+MB2
(2389)      J01 = J02-1
(2390)      SUMX(1) = 0.0
(2391)      SUMX(2) = 0.0

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(2392)      DO 185 K=1,N
(2393)      K2 = 2*K
(2394)      K1 = K2-1
(2395)      SUMX(1) = SUMX(1)+YHALF(I,K1)*ZHALF(K,J1)-YHALF(I,K2)*ZHALF(K,J2)
(2396)      SUMX(2) = SUMX(2)+YHALF(I,K1)*ZHALF(K,J2)+YHALF(I,K2)*ZHALF(K,J1)
(2397) 185  CONTINUE
(2398)      TABLX(I0,J01) = SUMX(1)
(2399)      TABLX(I0,J02) = SUMX(2)
(2400) 184  CONTINUE
(2401)  C   FOR          L = 1          2
(2402)  C   STORE          B1          C1
(2403)      DO 186 I=1,N
(2404)      I1 = I+MB
(2405)      DO 186 J=1,N
(2406)      J2 = 2*J
(2407)      J1 = J2-1
(2408)      XHALF(I,J1) = 0.0
(2409)      XHALF(I,J2) = 0.0
(2410)      JB2 = J2+IB2
(2411)      JB1 = JB2-1
(2412)      DO 186 K=1,N
(2413)      KI = K+IB
(2414)      K2 = 2*KI
(2415)      K1 = K2-1
(2416)      XHALF(I,J1) = XHALF(I,J1)+TABLX(I1,K1)*TABLX(KI,JB1)-TABLX(I1,K2)
(2417)      +                                *TABLX(KI,JB2)
(2418)      XHALF(I,J2) = XHALF(I,J2)+TABLX(I1,K1)*TABLX(KI,JB2)+TABLX(I1,K2)
(2419)      +                                *TABLX(KI,JB1)
(2420) 186  CONTINUE
(2421)      IF(JDIAG.EQ.5) CALL MOUTC(XHALF,N,N,M20,JR,JR,IROW,ICOL,LINE,KW)
(2422)      DO 188 I=1,N
(2423)      DO 188 J=1,N
(2424)      J2 = 2*J
(2425)      J1 = J2-1
(2426)      SUMX(1) = 0.0
(2427)      SUMX(2) = 0.0
(2428)      DO 189 K=1,N
(2429)      K2 = 2*K
(2430)      K1 = K2-1
(2431)      SUMX(1) = SUMX(1)-YHALF(I,K1)*XHALF(K,J1)+YHALF(I,K2)*XHALF(K,J2)
(2432)      SUMX(2) = SUMX(2)-YHALF(I,K1)*XHALF(K,J2)-YHALF(I,K2)*XHALF(K,J1)
(2433) 189  CONTINUE
(2434)      TABLX(I+MB,J1+IB2) = SUMX(1)
(2435)      TABLX(I+MB,J2+IB2) = SUMX(2)
(2436) 188  CONTINUE
(2437)      IF (ID.EQ.1) GO TO 190
(2438) 160  CONTINUE
(2439) 190  DLX(1) = DRE
(2440)      DLX(2) = DIM
(2441)      IF (JDIAG.NE.5) GO TO 200
(2442)      CALL MOUTC(TABLX,N2,N2,M60,JR,JR,IROW,ICOL,LINE,KW)
(2443)      WRITE(KW,1100)DLX(1),DLX(2)
(2444) 200  RETURN
(2445)      END

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(2446)      SUBROUTINE HEAD1
(2447)      INTEGER TITLE(16)
(2448)      COMMON/CHEAD1/TITLE,L1,L2,L3,L4,L5,LIST/WR/KW,KR
(2449)      WRITE(KW,1) TITLE,L1,L2,L3,L5
(2450)  1    FORMAT (1H1,T4,16A4//T10,14HSHAFT SEGMENTS,T38,1H=,T40,I5/T10,
(2451)      +15HSHAFT MATERIALS,T38,1H=,T40,I5/T10,15HLUMPED INERTIA
(2452)      +8HSTATIONS,T38,1H=,T40,I5/
(2453)      +T10,8HBEARINGS,T38,1H=,T40,I5)
(2454)      RETURN
(2455)      END

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(2456)      SUBROUTINE STAT(J,K)
(2457)      COMMON/ATEST1/B1(75),B2(75),B3(75),B4(75),B5(75),B6(75)
(2458)      COMMON/ATEST2/UO(80,4)
(2459)      COMMON/CSTAT/X(75),Z(76)
(2460)      DIMENSION D(4)
(2461)      KMJ=K-J
(2462)      KP1=K+1
(2463)      DO 1 L=1,4
(2464)      D(L)=UO(K,L)
(2465)      IF(L.GE.3) D(L)=D(L)*B2(KMJ)
(2466) 1      UO(KP1,L)=D(L)
(2467)      C = 1
(2468)      DO 4 L=1,4
(2469)      C=C*X(KMJ)/L
(2470)      IF (L.EQ.4) GO TO 4
(2471)      LL1 = 4-L
(2472)      DO 3 I=1,LL1
(2473)      IP1=I+L
(2474) 3      UO(KP1,IP1)=UO(KP1,IP1)+D(I)*C
(2475) 4      UO(KP1,L)=UO(KP1,L)-B1(KMJ)*C
(2476)      DO 5 L=3,4
(2477) 5      UO(KP1,L)=UO(KP1,L)/B2(KMJ)
(2478)      RETURN
(2479)      END

```

```

(2480)      SUBROUTINE STEP (K,IS,IER)
(2481)      INTEGER TITLE(16)
(2482)      COMMON/ATEST1/B1(75),B2(75),B3(75),B4(75),B5(75),B6(75)
(2483)      COMMON/ATEST3/YO(80,8),A5(80,8,4)
(2484)      COMMON/BSTEP/D5(4,2)
(2485)      COMMON/CSTAT/X(75),Z(76)
(2486)      COMMON/ACOU/S4(4),A6(4,6)
(2487)      COMMON/ABRG/S5(4,2),T5(4,2)
(2488)      COMMON/CHAD1/TITLE,L1,L2,L3,L4,L5,LIST/WR/KW,KR
(2489)      COMMON/ASTEP/J4,LB,M5,H5(4)
(2490)      DIMENSION D(4)
(2491)      K1 = K
(2492)      KK = K-J4
(2493)      KP = K+1
(2494)      DO 50 I=1,2
(2495)      I3 = 1-1
(2496)      I2 = 2*I3
(2497)      I4 = 2*I2
(2498)      I3 = 3*I3
(2499)      DO 40 M=1,3
(2500)      MM = M+I2-1
(2501)      DO 3 IL=1,4
(2502)      LL = IL+I4
(2503)      IF (M-2) 1,2,2
(2504) 1      D(IL) = YO(K1,LL)
(2505)      GO TO 3
(2506) 2      D(IL) = A5(K,LL,MM)
(2507) 3      CONTINUE
(2508)      IF (IS-2) 10,20,30
(2509) 10     DO 11 IL=3,4
(2510) 11     D(IL) = D(IL)*B2(KK)
(2511)      CALL TRANS (D,KK)
(2512)      IF (M.EQ.1.AND.I.EQ.1) CALL WT (D,KK)
(2513)      DO 14 IL=1,4
(2514)      IF (IL.GE.3) D(IL) = D(IL)/B2(KK)
(2515)      LL = IL+I4
(2516)      IF (M-2) 12,13,13
(2517) 12     YO(KP,LL) = D(IL)
(2518)      GO TO 14
(2519) 13     A5(KP,LL,MM) = D(IL)
(2520) 14     CONTINUE
(2521)      GO TO 40
(2522) 20     JJ = M+I3
(2523)      CALL HINGE (D,JJ)
(2524)      GO TO 40
(2525) 30     CALL BEAR (D,I)
(2526)      IF (M.EQ.1) D(1) = D(1)+S5(LB,I)*D5(LB,I)
(2527)      DO 33 IL=1,4
(2528)      LL = IL+I4
(2529)      IF (M-2) 31,32,32
(2530) 31     YO(K,LL) = D(IL)
(2531)      GO TO 33
(2532) 32     A5(K,LL,MM) = D(IL)
(2533) 33     CONTINUE

```

```

(2534) 40    CONTINUE
(2535)      IF (IS-2) 50,41,50
(2536) 41    I31 = I3+1
(2537)      I32 = I3+2
(2538)      I33 = I3+3
(2539)      AAA = A6(J4,I32)
(2540)      IF (AAA.EQ.0) GO TO 70
(2541)      A6(J4,I31) = -A6(J4,I31)/AAA
(2542)      A6(J4,I32) = -A6(J4,I33)/AAA
(2543)      A6(J4,I33) = S4(J4)/AAA
(2544)      I21 = I2+1
(2545)      I22 = I2+2
(2546)      DO 42 IL=1,4
(2547)      LL = IL+14
(2548)      IF (IL.EQ.3) GO TO 42
(2549)      A5(KP,LL,I22) = A5(K,LL,I21)*A6(J4,I32)+A5(K,LL,I22)
(2550)      A5(KP,LL,I21) = A5(K,LL,I21)*A6(J4,I33)
(2551)      V0(KP,LL) = V0(K1,LL)+A5(K,LL,I21)*A6(J4,I31)
(2552) 42    CONTINUE
(2553)      I+3 = I4+3
(2554)      A5(KP,I43,I21) = 0
(2555)      A5(KP,I43,I22) = 1
(2556) 50    CONTINUE
(2557)      IF (IS.NE 3.OR LB.EQ.L5) GO TO 60
(2558)      LB = LB+1
(2559)      M5 = M5(LB)
(2560) 60    RETURN
(2561) 70    WRITE (KW,71) J4
(2562) 71    FORMAT (/22H FREE COUPLING AT NODE,I3,19H SHOULD BE PRECEDED,
(2563)      +14H BY A BEARING.)
(2564)      IER = 1
(2565)      GOTO 60
(2566)      END

```



```

(2567)      SUBROUTINE BEAR (A,K)
(2568)      COMMON/BSTEP/D5(4,2)
(2569)      COMMON/ABRG/S5(4,2),T5(4,2)
(2570)      COMMON/ASTEP/J4,LB,M5,N5(4)
(2571)      DIMENSION A(4),BB(2)
(2572)      BB(1) = -S5(LB,K)
(2573)      BB(2) = T5(LB,K)
(2574)      DO 1 I=1,2
(2575)      J = 5-I
(2576)      1  A(I) = A(I)+BB(I)*A(J)
(2577)      RETURN
(2578)      END

```

```
(2579)      FUNCTION KFCN(N,K,I)
(2580)      KFCN = N*(K-1)+I
(2581)      RETURN
(2582)      END
```

```
(2583)      SUBROUTINE JFCN (J,N)
(2584)      COMMON/IIHIN/N1(5),N2(5)
(2585)      COMMON/ASTEP/J4,LB,M5,N5(4)
(2586)      J4 = J-1
(2587)      N = N1(J)
(2588)      RETURN
(2589)      END
```

```
(2590)      SUBROUTINE MFCH (J,H,M)
(2591)      COMMON/IMIN/N1(5),N2(5)
(2592)      N = N2(J)
(2593)      M = N+1
(2594)      RETURN
(2595)      END
```

```
PROGRAM SIZE:  PROCEDURE - 000020
0000 ERRORS [(MFCH >FTN-REV15.3]
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LINKAGE - 000022
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STACK - 000024
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```

(2596)      SUBROUTINE STACK (I,J,K,N,I1,K1,K2)
(2597)      DIMENSION N(4),K1(5),K2(5)
(2598)      I1=I-1
(2599)      IF (I1.GT.0) GO TO 3
(2600)      K1(I) = 1
(2601)      IF (K.GT.0) GO TO 2
(2602)  1     K2(I) = J+K
(2603)      GO TO 4
(2604)  2     K2(I) = N(I)+I1-1
(2605)      GO TO 4
(2606)  3     K1(I) = N(I1)+I1
(2607)      IF (K.GT.I1) GO TO 2
(2608)      GO TO 1
(2609)  4     RETURN
(2610)      END

```

```

(2611)      SUBROUTINE TRANS (A, KK)
(2612)      COMMON/CSTAT/X(75),Z(76)
(2613)      DIMENSION A(4),G(3)
(2614)      X1 = X(KK)
(2615)      XX = 1
(2616)      DO 1 M=1,3
(2617)      XX = XX*X1/M
(2618) 1      G(M) = XX
(2619)      DO 3 I=1,3
(2620)      M = 5-I
(2621)      MM = M-1
(2622)      DO 2 J=1,MM
(2623)      K = M-J
(2624)      B = G(J)*A(K)
(2625) 2      A(M) = A(M)+B
(2626) 3      CONTINUE
(2627)      RETURN
(2628)      END

```

```

(2629)      SUBROUTINE UT (D, KK)
(2630)      COMMON/ATEST1/B1(75),D2(75),B3(75),B4(75),B5(75),B6(75)
(2631)      COMMON/CSTAT/X(75),Z(76)
(2632)      DIMENSION D(4)
(2633)      BB = B1(KK)
(2634)      X1 = X(KK)
(2635)      DO 1 I=1,4
(2636)      BB = BB*X1/I
(2637) 1      D(I) = D(I)-BB
(2638)      RETURN
(2639)      END

```

```
(2640)      SUBROUTINE HINGE (A,JJ)
(2641)      COMMON/ACOU/S4(4),A6(4,6)
(2642)      COMMON/ASTEP/J4,LB,M5,N5(4)
(2643)      DIMENSION A(4)
(2644)      A6(J4,JJ) = A(2)+S4(J4)*A(3)
(2645)      RETURN
(2646)      END
```



```

(2647) SUBROUTINE TORS (K,D)
(2648) INTEGER TITLE(16)
(2649) COMMON/AWH/F,FF,XS(4,2),F1,FF1,SS
(2650) COMMON/ATEST1/B1(75),B2(75),B3(75),B4(75),B5(75),B6(75)
(2651) COMMON/CSTAT/X(75),Z(76)
(2652) COMMON/ASTEP/J4,LB,M5,N5(4)
(2653) COMMON/CHEAD1/TITLE,L1,L2,L3,L4,L5,LIST/WR/KW,KR
(2654) DIMENSION D(2)
(2655) KK=K-J4
(2656) 10 CC = FF*B4(KK)
(2657) AA = B5(KK)*CC
(2658) D(1)=D(1)/AA
(2659) CALL TWIST(D,KK,CC)
(2660) D(1) = D(1)*AA
(2661) 30 RETURN
(2662) END

```

```

(2663)      SUBROUTINE TWIST(D,K,C)
(2664)      INTEGER TITLE(16)
(2665)      COMMON/CSTAT/X(75),Z(76)
(2666)      COMMON/CHEAD1/TITLE,L1,L2,L3,L4,L5,LIST/WR/KW,KR
(2667)      DIMENSION D(2)
(2668)      C1=C*X(K)
(2669)      A = COS(C1)
(2670)      B = SIN(C1)
(2671)      E=A*D(1)-B*D(2)
(2672)      D(2)=B*D(1)+A*D(2)
(2673)      D(1)=E
(2674)      RETURN
(2675)      END

```

```

(2676)      SUBROUTINE BEND
(2677)      INTEGER TITLE(16)
(2678)      COMMON/AMH/F,FF,XS(4,2),F1,FF1,SS
(2679)      COMMON/ATEST1/B1(75),B2(75),B3(75),B4(75),B5(75),B6(75)
(2680)      COMMON/ATEST2/UO(80,4)
(2681)      COMMON/CSTAT/X(75),Z(76)
(2682)      COMMON/AEND/U(80,2),ZN(76),ZK(20),FFRT
(2683)      COMMON/CHEAD1/TITLE,L1,L2,L3,L4,L5,LIST/WR/KW,KR
(2684)      DO 1 L=1,L1
(2685)      BB = FFRT*B3(L)*X(L)
(2686)      CS = COS(BB)
(2687)      SN = SIN(BB)
(2688)      XH = EXP(BB)
(2689)      XO = 1.0/XH
(2690)      CH = 0.5*(XH+XO)
(2691)      SH = CH-XO
(2692)      UO(L,1) = 0.5*(CS+CH)
(2693)      UO(L,2) = 0.5*(SH-SN)
(2694)      UO(L,3) = UO(L,1)-CS
(2695)      UO(L,4) = UO(L,2)+SN
(2696)      RETURN
(2697)      END

```

```

(2698)      SUBROUTINE MODE
(2699)      COMMON/ABEND/U(80,2),ZM(76),ZK(20),FFRT
(2700)      COMMON/ABEND/L1P,L4P1,I8,I5
(2701)      MO=1
(2702)      A=ZM(1)*ZM(1)
(2703)      DO 1 I=2,L1P
(2704)      B=ZM(I)*ZM(I)
(2705)      IF(A.GE.B) GO TO 1
(2706)      MO=I
(2707)      A=B
(2708) 1      CONTINUE
(2709)      A = A/ZM(MO)
(2710)      DO 2 I=1,L1P
(2711) 2      ZM(I)=ZM(I)/A
(2712)      RETURN
(2713)      END

```

```

(2714)      SUBROUTINE COUP (M1,B)
(2715)      COMMON/AVIB/AA5(80,8,4)
(2716)      COMMON/ACOU/S4(4),A6(4,6)
(2717)      COMMON/ASTEP/J4,LB,M5,N5(4)
(2718)      DIMENSION D(8,4),B(4,4)
(2719)      DO 1 K=1,8
(2720)      DO 1 K1=1,4
(2721)  1      D(K,K1) = AA5(M1,K,K1)
(2722)      DO 5 K=1,8
(2723)      DO 5 K1=1,4
(2724)      IF (K.NE.3.AND K.NE.7) GO TO 3
(2725)      KK = 2*K1+1
(2726)      IF (K.EQ.KK) GO TO 2
(2727)      AA5(M1,K,K1) = 0.0
(2728)      GO TO 5
(2729)  2      AA5(M1,K,K1) = 1.0
(2730)      GO TO 5
(2731)  3      DO 4 K2=1,2
(2732)      KK = 2*K2-1
(2733)  4      AA5(M1,K,K1) = AA5(M1,K,K1)+D(K,KK)*B(K2,K1)
(2734)  5      CONTINUE
(2735)      RETURN
(2736)      END

```

```

(2737)      SUBROUTINE COUP1 (M,L,A,B)
(2738)      COMMON/AVIB/AA5(80,8,4)
(2739)      COMMON/ACOU/S4(4),A6(4,6)
(2740)      DIMENSION A(4,2,2),B(8),C(2),AA(2)
(2741)      C(1) = -B(2)-S4(L)*B(3)
(2742)      C(2) = -B(6)-S4(L)*B(7)
(2743)      DO 1 I=1,2
(2744)      AA(I) = 0
(2745)      DO 1 J=1,2
(2746) 1      AA(I) = AA(I)+A(L,I,J)*C(J)
(2747)      DO 2 I=1,8
(2748)      DO 2 J=1,2
(2749)      K = 2*J-1
(2750) 2      B(I) = B(I)+AA5(M,I,K)*AA(J)
(2751)      RETURN
(2752)      END

```

```

(2753)      SUBROUTINE LUMP (A,B,C,D,BB)
(2754)      DIMENSION BB(8)
(2755)      DO 1 K=1,2
(2756)      K1 = KFCN(4,K,1)
(2757)      K2 = KFCN(4,K,2)
(2758)      K3 = KFCN(4,K,3)
(2759)      K4 = KFCN(4,K,4)
(2760)      BB(K1) = BB(K1)+A*BB(K4)+B*BB(K3)
(2761)      AA = D
(2762)      IF (K.EQ.2) AA = -AA
(2763)      1 BB(K2) = BB(K2)-B*BB(K4)+(AA-C)*BB(K3)
(2764)      RETURN
(2765)      END

```

```
(2766)      SUBROUTINE LUMP1 (W,Y,T,P,F,G,A,B,C,D)
(2767)      A = G*W/386.4
(2768)      B = A*Y
(2769)      C = B*Y+G*T
(2770)      D = F*P
(2771)      RETURN
(2772)      END
```



```

(2773)      SUBROUTINE LIMP (M,A,B)
(2774)      COMMON/AVIB/AA5(80,8,4)
(2775)      COMMON/ACOU/S4(4),A6(4,6)
(2776)      COMMON/ASTEP/J4,LB,M5,N5(4)
(2777)      DIMENSION A(4,4),B(4,4)
(2778)      DO 2 I=1,2
(2779)      K = KFCN(4,I,2)
(2780)      L = K+1
(2781)      DO 2 J=1,2
(2782)      J2 = 2*J
(2783)      J1 = J2-1
(2784)      B(I,J2) = -AA5(M,L,J2)-S4(J4)*AA5(M,L,J2)
(2785)      IF (I.EQ.J) GO TO 1
(2786)      B(I,J1) = 0
(2787)      GO TO 2
(2788) 1      B(I,J1) = S4(J4)
(2789) 2      A(I,J) = AA5(M,K,J1)+S4(J4)*AA5(M,L,J1)
(2790)      KA = 2
(2791)      KB = 4
(2792)      IMAX = 4
(2793)      CALL MAXIV(A,KA,B,KB,DETERM,IMAX)
(2794)      RETURN
(2795)      END

```

(2796)		SUBROUTINE FLEX (K,F,E)
(2797)		COMMON/ATEST1/B1(75),B2(75),B3(75),B4(75),B5(75),B6(75)
(2798)		DIMENSION E(4)
(2799)		B = F*B3(K)
(2800)		E(1) = 1
(2801)		DO 2 I=2,4
(2802)		J = I-1
(2803)		A = E(J)
(2804)		IF (J-2) 2,1,2
(2805)	1	A = A*B2(K)
(2806)	2	E(I) = A*B
(2807)		RETURN
(2808)		END

```

(2809)      SUBROUTINE CFLEX (K,Θ,E)
(2810)      COMMON/ATEST2/UO(80,4)
(2811)      DIMENSION D(4),E(4),B(8),F(8)
(2812)      DO 1 I=1,4
(2813) 1      D(I) = UO(K,I)
(2814)      DO 5 J=1,4
(2815)      DO 3 L=1,2
(2816)      I = KFCN(4,L,J)
(2817)      A = 0
(2818)      DO 2 N=1,4
(2819)      M = KFCN(4,L,N)
(2820) 2      A = A+D(N)*E(M)*B(M)
(2821) 3      F(I) = A/E(J)
(2822)      IF (J.EQ.4) GO TO 5
(2823)      A = D(4)
(2824)      DO 4 N=1,3
(2825)      L = 5-N
(2826)      I = L-1
(2827) 4      D(L) = D(I)
(2828)      D(1) = A
(2829) 5      CONTINUE
(2830)      DO 6 I=1,8
(2831) 6      B(I) = F(I)
(2832)      RETURN
(2833)      END

```

```

(2834)      SUBROUTINE MAXIV(AS,N,BS,M,DS,NJ)
(2835)      C
(2836)      C   MATRIX INVERSION AND SOLUTION OF SIMULTANEOUS LINEAR EQUATIONS
(2837)      C   OF THE FORM      AS*X=BS
(2838)      C   INV(AS) AND X ARE RETURNED AS (AS,BS), THE ORIGINAL (AS,BS) ARE
(2839)      C   LOST
(2840)      C   N<.LT.61) RANK OF AS AND BS, RETURNED AS 0 IF AS IS SINGULAR
(2841)      C   M      COLUMNS OF BS, M MUST NOT EXCEED N
(2842)      C   DS      DETERMINANT OF AS
(2843)      C   AS AND BS MUST BE DIMENSIONED (NJ,NJ) IN THE CALLING PROGRAM
(2844)      C   NJ MUST BE NO LESS THAN EITHER M OR N
(2845)      C
(2846)      C   DIMENSION A1(60,60),PIVOT(60)
(2847)      C   DIMENSION AS(NJ,1),BS(NJ,1)
(2848)      C   DIMENSION IPIVOT(20),INDEX(20,2)
(2849)      C   EQUIVALENCE (IROW,JROW), (ICOLUM,JCOLUM), (AMAX,T,SWAP)
(2850)      C
(2851)      C   COMPUTATION OF NORM
(2852)      C
(2853)      1   C = 1.0E-20
(2854)      2   ANO = 0.0
(2855)      3   DO 6 I=1,N
(2856)      4   DO 6 J=1,N
(2857)      5   ANO = ANO+AS(I,J)*AS(I,J)
(2858)      6   A1(I,J) = AS(I,J)
(2859)      7   ANO = ANO/N
(2860)      C
(2861)      C   INITIALIZATION
(2862)      C
(2863)      10  DETERM = 1.0
(2864)      15  DO 20 J=1,N
(2865)      20  IPIVOT(J) = 0
(2866)      30  DO 550 I=1,N
(2867)      C
(2868)      C   SEARCH FOR PIVOT ELEMENT
(2869)      C
(2870)      40  AMAX = 0.0
(2871)      45  DO 100 J=1,N
(2872)      50  IF (IPIVOT(J) EQ 1) GO TO 100
(2873)      60  DO 100 K=1,N
(2874)      70  IF (IPIVOT(K)-1) 80,100,840
(2875)      80  IF (ABS(AMAX)-ABS(AS(J,K))) 85,100,100
(2876)      85  IROW = J
(2877)      90  ICOLUM = K
(2878)      95  AMAX = AS(J,K)
(2879)      100 CONTINUE
(2880)      110 IPIVOT(ICOLUM) = IPIVOT(ICOLUM)+1
(2881)      C
(2882)      C   INTERCHANGE ROWS TO PUT PIVOT ELEMENT ON DIAGONAL
(2883)      C
(2884)      130 IF (IROW.EQ.ICOLUM) GO TO 260
(2885)      140 DETERM = -DETERM
(2886)      150 DO 200 L=1,N
(2887)      160 SWAP = AS(IROW,L)

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(2888) 170 AS(IROW,L) = AS(ICOLUM,L)
(2889) 200 AS(ICOLUM,L) = SWAP
(2890) 205 IF (M.LE.0) GO TO 260
(2891) 210 DO 250 L=1,M
(2892) 220 SWAP = BS(IROW,L)
(2893) 230 BS(IROW,L) = BS(ICOLUM,L)
(2894) 250 BS(ICOLUM,L) = SWAP
(2895) 260 INDEX(I,1) = IROW
(2896) 270 INDEX(I,2) = ICOLUM
(2897) 310 PIVOT(I) = AS(ICOLUM,ICOLUM)
(2898) 320 DETERM = DETERM*PIVOT(I)
(2899) C
(2900) C ROW NORMALIZATION
(2901) C
(2902) 330 AS(ICOLUM,ICOLUM)=1.0
(2903) 340 DO 350 L=1,N
(2904) 350 AS(ICOLUM,L) = AS(ICOLUM,L)/PIVOT(I)
(2905) 355 IF (M.LE.0) GO TO 380
(2906) 360 DO 370 L=1,M
(2907) 370 BS(ICOLUM,L) = BS(ICOLUM,L)/PIVOT(I)
(2908) C
(2909) C REDUCE NON-PIVOT ROWS
(2910) C
(2911) 380 DO 550 L1=1,N
(2912) 390 IF (L1.EQ.ICOLUM) GO TO 550
(2913) 400 T = AS(L1,ICOLUM)
(2914) 420 AS(L1,ICOLUM) = 0.0
(2915) 430 DO 450 L=1,N
(2916) 450 AS(L1,L) = AS(L1,L)-AS(ICOLUM,L)*T
(2917) 455 IF (M.LE.0) GO TO 550
(2918) 460 DO 500 L=1,M
(2919) 500 BS(L1,L) = BS(L1,L)-BS(ICOLUM,L)*T
(2920) 550 CONTINUE
(2921) C
(2922) C INTERCHANGE COLUMNS
(2923) C
(2924) 600 DO 720 I=1,N
(2925) 610 L = N+1-I
(2926) 620 IF (INDEX(L,1) EQ. INDEX(L,2)) GO TO 720
(2927) 630 JROW = INDEX(L,1)
(2928) 640 JCOLUM = INDEX(L,2)
(2929) 650 DO 710 K=1,N
(2930) 660 SWAP = AS(K,JROW)
(2931) 670 AS(K,JROW) = AS(K,JCOLUM)
(2932) 700 AS(K,JCOLUM) = SWAP
(2933) 710 CONTINUE
(2934) 720 CONTINUE
(2935) C
(2936) C TEST SINGULARITY
(2937) C
(2938) 730 DO 780 I=1,N
(2939) 740 D = 0.0
(2940) 750 DO 760 J=1,N
(2941) 760 D = D+A1(I,J)*AS(J,I)

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(2942) 770  DETERM = D*DETERM
(2943) 780  CONTINUE
(2944) 790  DETERM = DETERM*DETERM
(2945) 800  DO 810 I=1,N
(2946) 810  DETERM = DETERM/ANO
(2947) 820  IF (DETERM.LT.C) GO TO 840
(2948) 830  DS = DETERM
(2949)      RETURN
(2950)  C
(2951)  C  SET ERROR INDEX FOR SINGULAR INPUT MATRIX
(2952)  C
(2953) 840  N = 0
(2954) 850  GO TO 830
(2955)      END

```

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(2956)      SUBROUTINE ISTRP(ISO,IBRG,STIF,DAMP,IRUN)
(2957)      DIMENSION STIF(2,2,20),DAMP(2,2,20)
(2958)      ISO=0
(2959)      IF (IBRG.EQ.0) GO TO 105
(2960)      DO 101 I=1,IBRG
(2961)      ANORM=STIF(1,1,I)**2+STIF(2,2,I)**2+STIF(1,2,I)**2+STIF(2,1,I)**2
(2962)      BNORM=DAMP(1,1,I)**2+DAMP(2,2,I)**2+DAMP(1,2,I)**2+DAMP(2,1,I)**2
(2963)      ASUM=(STIF(1,2,I)+STIF(2,1,I))*2+(STIF(1,1,I)-STIF(2,2,I))*2
(2964)  101   BSUM=(DAMP(1,2,I)+DAMP(2,1,I))*2+(DAMP(1,1,I)-DAMP(2,2,I))*2
(2965)      TNORM=ANORM+BNORM
(2966)      IF (TNORM.EQ.0.0) GO TO 105
(2967)      RTOR=(ASUM+BSUM)/TNORM
(2968)      IF (RTOR.GT.1.00-8) ISO=1
(2969)  105   RETURN
(2970)      END

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(2971)      SUBROUTINE IGHRL(NBEND,INDEX,ISO,DETER,IWARN)
(2972)      COMMON/BMAT/XLX(60,120),YLX(60,120),ZLX(60,120),
(2973)      +XHALF(20,40),YHALF(20,40),ZHALF(20,40),QHALF(20,40)
(2974)      COMMON/BINV/XIN(60,122),XOU(60,122),DLX(2),IROW(61),ICOL(61)
(2975)      COMMON/WUADD/FSQ
(2976)      DIMENSION DETER(2,1),IWARN(2,2)
(2977)      IONE = 1
(2978)      ITWO = 2
(2979)      L=ISO*NBEND
(2980)      I20 = 20
(2981)      GSQ = 39.478417604*FSQ
(2982)      DO 91 I=1,NBEND
(2983)      DO 91 K=1,NBEND
(2984)      J = 2*K-1
(2985)      IF (ISO.EQ.0) GO TO 91
(2986)      J1 = J+2*NBEND
(2987)      YHALF(I,K) = -YLX(I,J1)/GSQ
(2988) 91      XHALF(I,K) = YLX(I,J)/GSQ
(2989)      NIN = NBEND
(2990)      CALL MAXIV(XHALF,NIN,YHALF,L,DETER(IONE,INDEX),I20)
(2991)      IF (NIN.GT.0) GO TO 92
(2992)      IW=1
(2993)      GO TO 93
(2994) 92      IW=0
(2995)      L=0
(2996) 93      IWARN(1,INDEX)=IW
(2997)      DO 95 I=1,NBEND
(2998)      I1=I+NBEND
(2999)      DO 95 K=1,NBEND
(3000)      J = 2*K-1
(3001)      J1 = J+2*NBEND
(3002)      XHALF(I,K) = YLX(I1,J1)/GSQ
(3003)      IF (ISO.EQ.0) GO TO 95
(3004)      IF (IW.EQ.0) GO TO 101
(3005)      YHALF(I,K) = -YLX(I1,J)/GSQ
(3006)      GO TO 95
(3007) 101      DO 94 M=1,NBEND
(3008)      M1 = 2*M-1
(3009)      XHALF(I,K) = XHALF(I,K)+YLX(I1,M1)*YHALF(M,K)/GSQ
(3010) 94      CONTINUE
(3011) 95      CONTINUE
(3012)      NIN = NBEND
(3013)      CALL MAXIV(XHALF,NIN,YHALF,L,DETER(ITWO,INDEX),I20)
(3014)      IF (NIN.GT.0) GO TO 102
(3015)      IWARN(2,INDEX)=1
(3016)      GO TO 200
(3017) 102      IWARN(2,INDEX)=0
(3018)      IF (ISO.EQ.0) GO TO 200
(3019)      IF (IW.EQ.0) GO TO 97
(3020)      DO 96 I=1,NBEND
(3021)      DO 96 M=1,NBEND
(3022)      J = 2*M-1
(3023)      XHALF(I,M) = YLX(I,J)/GSQ
(3024)      DO 96 K=1,NBEND

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(3025)      K1 = 2*(K+NBEND)-1
(3026)  96    XHALF(I,M) = XHALF(I,M)+YLX(I,K1)*YLX(K,J)/GSQ
(3027)      CALL MAXIV(XHALF,NBEND,YHALF,L,DETER(1,INDEX),I20)
(3028)  97    DETER(2,INDEX)=DETER(1,INDEX)*DETER(2,INDEX)
(3029)  200    RETURN
(3030)      END

```

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(3031)      SUBROUTINE ENTER(KS,KE,KW,NB,NF,IS,DT,F,SP,RT,XI,IR,IDG)
(3032)      INTEGER STEP,FINAL,DIRECT,POINT6,POINT7
(3033)      COMMON/CODA/K9(20)
(3034)      DIMENSION TABLX(60,122),CN(3,10),CO(4,10,40),DT(2,11),V(60),F(11),
(3035)      + SP(11),RT(11),XI(11),F1(4),SP1(4)
(3036)  C    SET UP FILE OF INTERPOLATION COEFFICIENTS
(3037)      DIRECT = 0
(3038)      REWIND KS
(3039)      REWIND KE
(3040)      MF=MF-1
(3041)      N10=NB+1
(3042)      N20=NB+NB
(3043)      N202 = 2*N20
(3044)      N1=1
(3045)      N2=NB
(3046)      NR = -1
(3047) 10    DO 70 I=N1,N2
(3048)        IO=I
(3049)        IF (I.LE.NB) GO TO 11
(3050)        ISTART = I-NB
(3051)        GO TO 12
(3052) 11      ISTART = I
(3053) 12      IF(IS.EQ.1.AND.N1.GE.N10) GO TO 60
(3054) 20      I1=I
(3055)        M2=N2
(3056) 30      CONTINUE
(3057)        DO 50 J=I1,M2
(3058)          J1 = 2*J-1
(3059)          REWIND KS
(3060)          DO 40 N=1,NF
(3061)            READ (KS) SO,F(N),((TABLX(L,M),M=1,N202),L=1,N20)
(3062) 40      SP(N) = TABLX(IO,J1)
(3063)            IER=0
(3064)            NPTS = NF
(3065)            CALL SPLINE(NR,NF,RT,XI,F,SP,CN,KW,IER)
(3066)            IF (IER.NE.0) GO TO 170
(3067)            DO 50 N=1,MF
(3068)              CO(1,N,J)=SP(N)
(3069)            DO 50 L=1,3
(3070)              M=L+1
(3071)              CO(M,N,J)=CN(L,N)
(3072) 50      CONTINUE
(3073)            IF(M2.EQ.N20) GO TO 56
(3074)            M2=N20
(3075)            I1=I
(3076)            IF(I1.LT.N10) I1=I1+NB
(3077)            IF(IS.EQ.0) IO=I1
(3078)            GO TO 30
(3079) 56      WRITE(KE) IS,((((CO(L,M,J),CO(L,M,J+NB)),L=1,4),J=ISTART,NB),
(3080)      +    M=1,MF)
(3081)            GO TO 70
(3082) 60      I1=I-NB
(3083)            M2=NB
(3084)            GO TO 30

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(3085) 70 CONTINUE
(3086) IF(1S.EQ.0.OR.N2.EQ.N20) GO TO 80
(3087) N1=N10
(3088) N2=N20
(3089) GO TO 10
(3090) 80 REWIND KE
(3091) IF(1S.EQ.1) GO TO 160
(3092) IROT=1
(3093) 100 DO 110 I=1,NF
(3094) 110 SP(I)=DT(IROT,I)
(3095) NR=0
(3096) IF(NF.LE.4) GOTO 300
(3097) POINT6=0
(3098) POINT7=0
(3099) IF(NF.NE.5) GOTO 6
(3100) 1 NF1=3
(3101) STEP=2
(3102) 3 NRO = 0
(3103) DO 2 I=1,NF1,STEP
(3104) NR1 = NRO+1
(3105) J=I+2+POINT7
(3106) IF(I.NE.3) GOTO 4
(3107) J=J+POINT6
(3108) JJ=1
(3109) DO 5 II=I,J
(3110) F1(JJ)=F(II)
(3111) SP1(JJ)=SP(II)
(3112) 5 JJ=JJ+1
(3113) NR=0
(3114) IER = 0
(3115) NPTS = NF1
(3116) CALL SPLINE(NR,NF1,RT,XI,F1,SP1,CN,KW,IER)
(3117) IF (IER.NE.0) GO TO 170
(3118) IF (NR.LE.0) GO TO 2
(3119) CALL ROOTAB(IR,IS,IROT,NR,RT,NB,NF,KE,KW,F1,CO,V.DIRECT,1DG)
(3120) NRO = NRO+NR
(3121) 2 CONTINUE
(3122) NR = NRO
(3123) GOTO 155
(3124) 6 IF(NF.NE.6) GOTO 7
(3125) POINT6=1
(3126) GOTO 1
(3127) 7 IF(NF.NE.7) GOTO 8
(3128) POINT7=1
(3129) STEP=3
(3130) NF1=4
(3131) GOTO 3
(3132) 8 NF2=NF-1
(3133) NRO = 0
(3134) DO 9 I=2,NF2
(3135) NR1 = NRO+1
(3136) ABSF=ABS(SP(I))
(3137) ABSF1=ABS(SP(I-1))
(3138) ABSF2=ABS(SP(I+1))

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(3139)      IF(ABSF GT ABSF1.OR.ABSF.GT.ABSF2) GOTO 9
(3140)      INC=I-1
(3141)      IF(ABSF1.LT.ABSF2) INC=I-2
(3142)      IF(INC.LT.1) INC=1
(3143)      JJ=1
(3144)  17    FINAL=INC+3
(3145)      IF(FINAL.LE.NF) GOTO 16
(3146)      INC=INC-1
(3147)      GOTO 17
(3148)  16    DO 18 II=INC,FINAL
(3149)          F1(JJ)=F(II)
(3150)          SP1(JJ)=SP(II)
(3151)  18    JJ=JJ+1
(3152)      NF1=4
(3153)      IER=0
(3154)      NR=0
(3155)      NPTS = NF1
(3156)      CALL SPLINE(NR,NF1,RT,XI,F1,SP1,CN,KW,IER)
(3157)      IF (IER.NE.0) GO TO 170
(3158)      IF (NR.LE.0) GO TO 9
(3159)      CALL ROOTAB(IR,IS,IROT,NR,RT,NB,NF,KE,KW,F1,CO,V,DIRECT,IDG)
(3160)      NRO = NRO+NR
(3161)  9      CONTINUE
(3162)      NR = NRO
(3163)      GOTO 155
(3164)  300    IER = 0
(3165)      INC = 1
(3166)      NPTS = NF
(3167)      CALL SPLINE(NR,NF,RT,XI,F,SP,CN,KW,IER)
(3168)      IF (IER.NE.0) GO TO 170
(3169)      IF (NR.LE.0) GO TO 155
(3170)      CALL ROOTAB(IR,IS,IROT,NR,RT,NB,NF,KE,KW,F,CO,V,DIRECT,IDG)
(3171)  155    IF (IS.EQ.1) GO TO 130
(3172)      IF (IROT.EQ.2) GO TO 120
(3173)      WRITE (KW,2000) NR
(3174)  2000   FORMAT(/29H NO OF CO-ROTATIONAL ROOTS =,I5/)
(3175)      GO TO 156
(3176)  120    WRITE(KW,2001) NR
(3177)  2001   FORMAT(/29H NO OF CTR-ROTATIONAL ROOTS =,I5/)
(3178)      GO TO 200
(3179)  130    WRITE (KW,2002) NR
(3180)  2002   FORMAT(/29H NO OF COUPLED ROOTS =,I5/)
(3181)      GO TO 200
(3182)  156    IF(DIRECT.EQ.20) GOTO 200
(3183)      IF((IROT.EQ. 2).OR.(IR.EQ.1.AND.IS.EQ.0)) GO TO 200
(3184)  160    IROT=2
(3185)      GO TO 100
(3186)  170    WRITE (KW,1000)
(3187)  200    RETURN
(3188)  1000   FORMAT (/49H ERROR ENCOUNTERED DURING EXECUTION OF SUBROUTINE,
(3189)      +8H SPLINE.)
(3190)      END

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(3191)      SUBROUTINE ROOTAB(IR,IS,IROT,HR,RT,NB,NF,KE,KW,F,CO,V,DIRECT,IDG)
(3192)      INTEGER DIRECT
(3193)      DIMENSION CO(4,10,1),RT(1),F(1),V(1)
(3194)      DIRECT=0
(3195)      IF (HR.EQ.0) GO TO 110
(3196)      IF (IS.EQ.1) GO TO 143
(3197)      IF (IROT-1) 140,140,142
(3198) 110    IF (IS.EQ.1.OR.IROT.EQ.2) GO TO 115
(3199)      DIRECT = 15
(3200)      GO TO 100
(3201) 115    DIRECT = 20
(3202) 140    WRITE(KW,1000)
(3203) 1000    FORMAT(/19H CO-ROTATIONAL MODE)
(3204) 141    IF (IR.EQ.1) GO TO 1141
(3205)      WRITE(KW,1001)
(3206) 1001    FORMAT(/20X,10H FRFQ (HZ),6X,42HLOCATION (IN) DEFLECTION
(3207)      +PE
(3208)      GO TO 145
(3209) 1141    WRITE (KW,1011)
(3210) 1011    FORMAT(/20X,10H      RPM      ,6X,42HLOCATION (IN) DEFLECTION
(3211)      +PE
(3212)      GO TO 145
(3213) 142    WRITE(KW,1002)
(3214) 1002    FORMAT(/20H CTR-ROTATIONAL MODE)
(3215)      GO TO 141
(3216) 143    WRITE(KW,1003)
(3217) 1003    FORMAT(/13H COUPLED MODE,38X,23HCO-ROTATIONAL COMPONENT,6X,
(3218)      +24HCTR-ROTATIONAL COMPONENT)
(3219)      IF (IR.EQ.1) GO TO 1143
(3220)      WRITE (KW,1004)
(3221) 1004    FORMAT(21X,10H FREQ (HZ),6X,13HLOCATION (IN),2(27H DEFLECTION
(3222)      +SLOPE      ,3X))
(3223)      GO TO 145
(3224) 1143    WRITE (KW,1014)
(3225) 1014    FORMAT(21X,10H      RPM      ,6X,13HLOCATION (IN),2(27H DEFLECTION
(3226)      +SLOPE      ,3X))
(3227) 145    DO 150 NP=1,NR
(3228)      RES=RT(NP)
(3229) 150    CALL BMODE (IR,IS,IROT,NB,NF,KW,KE,F,CO,RES,V,IDG)
(3230) 100    RETURN
(3231)      END

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(3232)      SUBROUTINE BMODE(IRUN,IS,IR,NB,NF,KW,KE,F,C,R,V,IDG)
(3233)      DIMENSION F(1),C(4,10,1),V(1),X(40,40),POSIT(76),M8(20),K8(20)
(3234)      +W(60)
(3235)      COMMON/WUS/M8,K8,X,POSIT
(3236)      COMMON/CODA/K9(20)
(3237)      N40 = 40
(3238)      RSQ = 39.47841760436*R*R
(3239)  C    GENERATE INTERPOLATED IMPEDANCE MATRIX
(3240)      MF=NF-1
(3241)      N20=NB+NB
(3242)      N2=NB+IS*NB
(3243)  10    DO 100 I=1,N2
(3244)      IF (I.LE.NB) GO TO 11
(3245)      ISTART = I-NB
(3246)      GO TO 12
(3247)  11    ISTART = I
(3248)  12    IF (IS.EQ.1 .AND. I.GT.NB) GO TO 90
(3249)      I1=I
(3250)      M2=NB
(3251)  25    READ (KE) IS,((((C(L,M,J),C(L,M,J+NB)),L=1,4),J=ISTART,NB),M=1,
(3252)      +MF)
(3253)  30    DO 90 J=I1,M2
(3254)      K=J
(3255)  35    IF (IS.EQ.1) GO TO 35
(3256)      IF (IR.EQ.2) K=K+NB
(3257)      DO 40 L=1,MF
(3258)      U=F(L)
(3259)      IF (R.GT.U) GO TO 40
(3260)      LQ=L
(3261)      GO TO 50
(3262)  40    CONTINUE
(3263)      L=MF
(3264)      GO TO 60
(3265)  50    IF (R.EQ.U) GO TO 70
(3266)      L=LQ-1
(3267)  60    D=R-F(L)
(3268)      X(I,J)=(C(1,L,K)+D*(C(2,L,K)+D*(C(3,L,K)+D*C(4,L,K))))/PSQ
(3269)  65    IF (J.EQ.I1) GO TO 80
(3270)      IF (I1-I) 71,72,73
(3271)  71    JO=J+NB
(3272)      IO=I-NB
(3273)      GO TO 75
(3274)  72    JO=J
(3275)      IO=I
(3276)      GO TO 75
(3277)  73    JO=J-NB
(3278)      IO=I+NB
(3279)  75    X(JO,IO)=X(I,J)
(3280)      GO TO 80
(3281)  70    X(I,J)=C(1,L,K)/RSQ
(3282)      GO TO 65
(3283)  80    CONTINUE
(3284)      IF (IS.EQ.0) GO TO 100
(3285)      IF (M2.EQ.N20) GO TO 100

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(3286)      M2=N20
(3287)      I1=I1+NB
(3288)      GO TO 30
(3289)  90   I1=I-NB
(3290)      M2=NB
(3291)      GO TO 25
(3292)  100  CONTINUE
(3293)      REWIND KE
(3294)  C    CALCULATE CHARACTERISTIC VECTOR
(3295)      IF (IDG.NE.4) GO TO 5101
(3296)      WRITE (KW,2000)
(3297)  2000 FORMAT (/30H INTERPOLATED STIFFNESS MATRIX//)
(3298)      CALL MATPRT(N2,N2,N40,N40,X)
(3299)  C    INVERT INTERPOLATED STIFFNESS MATRIX
(3300)  5101 IMAX = 0
(3301)      CALL MAXIV(X,N2,X,IMAX,DET,N40)
(3302)      IF (N2.GT.0) GO TO 5102
(3303)      WRITE (KW,51) R
(3304)  51   FORMAT (34H1EXACT RESONANCE IS ENCOUNTERED AT,1PD12.5.4H HZ,/
(3305)      +31H MODE SHAPE CANNOT BE COMPUTED.)
(3306)      GO TO 510
(3307)  5102 IF (IDG.NE.4) GO TO 81
(3308)      WRITE (KW,2001)
(3309)  2001 FORMAT (/18H MODE SHAPE MATPIX//)
(3310)      CALL MATPRT(N2,N2,N40,N40,X)
(3311)  C    SEARCH FOR LARGEST DIAGONAL ELEMENT OF THE MOBILITY MATRIY
(3312)  81   KMAX = 0
(3313)      DO 103 I=1,N2
(3314)      IF (K9(I).EQ.2) GO TO 103
(3315)      TRY = ABS(X(I,I))
(3316)      IF (KMAX.EQ.1) GO TO 101
(3317)      KMAX = 1
(3318)      GO TO 102
(3319)  101  IF (TRY.LE.AMAX) GO TO 103
(3320)  102  IX = I
(3321)      AMAX = TRY
(3322)  103  CONTINUE
(3323)  C    CALCULATE NORMALIZED MODE SHAPE
(3324)      AMAX = X(IX,IX)
(3325)      DO 104 I=1,N2
(3326)      V(I) = X(I,IX)/AMAX
(3327)  104  CONTINUE
(3328)  C    PRINT MODE SHAPE
(3329)      IF (IRUN.EQ.1) R = 60.0*R
(3330)      ITIME=1
(3331)      DO 500 I=1,NB
(3332)      N=M8(I)
(3333)      JT=K9(I)-2
(3334)      IF (JT.LE.2) GO TO 406
(3335)      IF (JT-5) 404,403,402
(3336)  402  JT=JT-1
(3337)  403  JT=JT-3
(3338)      IF (ITIME.EQ.2) GO TO 405
(3339)      ITIME=2

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(3340)      W1=V(I)
(3341)      IF (IS.EQ.0) GO TO 500
(3342)      I1=I+NB
(3343)      W3=V(I1)
(3344)      GO TO 500
(3345)  404  JT=JT-2
(3346)      GO TO 406
(3347)  405  ITIME=1
(3348)      W2=V(I)
(3349)      IF (IS.EQ.0) GO TO 410
(3350)      I1=I+NB
(3351)      W4=V(I1)
(3352)      IF (I.GT.1) GO TO 425
(3353)      WRITE (KW,1011) R,POSIT(N),W1,W2,W3,W4
(3354)  1011  FORMAT (20X,1PE11.4,5E15.4)
(3355)      GO TO 500
(3356)  425  WRITE(KW,1001) POSIT(N),W1,W2,W3,W4
(3357)  1001  FORMAT(31X,1P5E15.4)
(3358)      GO TO 500
(3359)  406  IF (JT.EQ.2) GO TO 408
(3360)      IF (IS.EQ.1) GO TO 407
(3361)      IF (I.GT.1) GO TO 426
(3362)      WRITE (KW,1011) R,POSIT(N),V(I)
(3363)      GO TO 500
(3364)  426  WRITE(KW,1001) POSIT(N),V(I)
(3365)      GO TO 500
(3366)  407  W1=V(I)
(3367)      W3=V(I+NB)
(3368)      IF (I.GT.1) GO TO 427
(3369)      WRITE (KW,1012) R,POSIT(N),W1,W3
(3370)  1012  FORMAT (20X,1PE11.4,2E15.4,15X,E15.4)
(3371)      GO TO 500
(3372)  427  WRITE(KW,1002) POSIT(N),W1,W3
(3373)  1002  FORMAT(31X,1P2E15.4,15X,E15.4)
(3374)      GO TO 500
(3375)  408  IF (IS.EQ.1) GO TO 409
(3376)      IF (I.GT.1) GO TO 428
(3377)      WRITE (KW,1013) R,POSIT(N),V(I)
(3378)  1013  FORMAT (20X,1PE11.4,2(E15.4,15X),E15.4)
(3379)      GO TO 500
(3380)  428  WRITE(KW,1003) POSIT(N),V(I)
(3381)      GO TO 500
(3382)  409  IF (I.GT.1) GO TO 429
(3383)      WRITE (KW,1011) R,POSIT(N),V(I),V(I+NB)
(3384)      GO TO 500
(3385)  429  WRITE(KW,1003) POSIT(N),V(I),V(I+NB)
(3386)  1003  FORMAT(16X,3(15X,1PE15.4))
(3387)      GO TO 500
(3388)  410  IF (I.GT.1) GO TO 430
(3389)      WRITE (KW,1011) R,POSIT(N),W1,W2
(3390)      GO TO 500
(3391)  430  WRITE(KW,1001) POSIT(N),W1,W2
(3392)  500  CONTINUE
(3393)  510  RETURN
(3394)      END

```



```

(3395)      SUBROUTINE MATPRT(M1,N1,M2,N2,DMAT)
(3396)      COMMON/WR/KW,KR
(3397)      DIMENSION DMAT(M2,N2)
(3398)      WRITE(KW,50)
(3399)      DO 10 I=1,M1
(3400) 10    WRITE(KW,100) (DMAT(I,J),J=1,N1)
(3401)      WRITE(KW,150)
(3402) 50    FORMAT(25H ***** START MATPRT *****/)
(3403) 100    FORMAT(1X,1P10E13.5)
(3404) 150    FORMAT(/25H ***** END MATPRT *****)
(3405)      RETURN
(3406)      END

```

```

(3407)      SUBROUTINE RUNCON(KW,IR,IT,ID,NT)
(3408)      DIMENSION ID(4),NT(16)
(3409)      WRITE (KW,10) ID,NT
(3410) 10    FORMAT (1H1,30(1H*),19H CALCULATION SUMMARY,30(1H*)//1H ,20A4)
(3411)      IF (IR.EQ.0) GO TO 50
(3412)      GO TO (100,200,300,400,500,600), IR
(3413) 50    WRITE (KW,20)
(3414) 20    FORMAT(/54H RSVP SUPPLEMENTARY DATA AND ORIGINAL IMPEDANCE MATRIC,
(3415)      +2HES)
(3416)      GO TO 700
(3417) 100   WRITE (KW,110)
(3418) 110   FORMAT (/27H CRITICAL SPEED CALCULATION)
(3419)      GO TO 700
(3420) 200   WRITE (KW,210)
(3421) 210   FORMAT (/19H UNBALANCE RESPONSE)
(3422)      GO TO 700
(3423) 300   WRITE (KW,310)
(3424) 310   FORMAT (/35H ASYNCHRONOUS RESONANCE CALCULATION)
(3425)      GO TO 700
(3426) 400   WRITE (KW,410)
(3427) 410   FORMAT (/22H ASYNCHRONOUS RESPONSE)
(3428)      IF (IT.EQ.1) GO TO 420
(3429)      WRITE (KW,411)
(3430) 411   FORMAT (36H EXCITATION IS OF THE ROTATING TYPE.)
(3431)      GO TO 700
(3432) 420   WRITE (KW,421)
(3433) 421   FORMAT (26H EXCITATION IS STATIONARY.)
(3434)      GO TO 700
(3435) 500   WRITE (KW,510)
(3436) 510   FORMAT (/25H WHIRL STABILITY ANALYSIS)
(3437)      GO TO 700
(3438) 600   WRITE (KW,610)
(3439) 610   FORMAT (/32H TORSIONAL RESONANCE CALCULATION)
(3440) 700   RETURN
(3441)      END

```

```

(3442)      SUBROUTINE BRGTAB(KW,I,KBO,NB,KB,IT,KZ,T,B,O)
(3443)      DIMENSION T(2,1),B(2,1),C(2,4)
(3444)      IF (NB-KZ) 1,3,2
(3445) 1      MB = KZ
(3446)      GO TO 4
(3447) 2      LB = KB
(3448)      MB = NB
(3449)      GO TO 6
(3450) 3      MB = NB
(3451) 4      LB = IT
(3452)      DO 5 IZ=1,2
(3453)      DO 5 JZ=1,2
(3454)      JZ2 = 2*JZ
(3455)      JZ1 = JZ2-1
(3456)      C(IZ,JZ1) = B(IZ,JZ)
(3457)      C(IZ,JZ2) = 0.0
(3458)      IF (KB.NE.IT.OR.NB.NE.KZ) GO TO 5
(3459)      C(IZ,JZ1) = C(IZ,JZ1)+T(IZ,JZ1)
(3460)      C(IZ,JZ2) = C(IZ,JZ2)+T(IZ,JZ2)/O
(3461) 5      CONTINUE
(3462)      GO TO 8
(3463) 6      DO 7 IZ=1,2
(3464)      DO 7 JZ=1,4
(3465)      TO = T(IZ,JZ)
(3466)      JZ1 = 2*(JZ/2)
(3467)      IF (JZ1.EQ.JZ) TO = TO/O
(3468)      C(IZ,JZ) = TO
(3469) 7      CONTINUE
(3470)      GO TO (10,20), LB
(3471)      WRITE (KW,9) KB,I
(3472) 9      FORMAT (/35H ERROR MESSAGE **** VALUE OF KBRG (,I3,I2H) AT BRG NO.
(3473)      +,I3,35H IS ILLEGAL. COMPUTATION IS HALTED.)
(3474)      CALL EXIT
(3475) 8      IF (LB.EQ.2) GO TO 20
(3476) 10     WRITE(KW,11) KBO,MB,((C(M,N),N=1,4),M=1,2)
(3477) 11     FORMAT (I3,I4,5X,1H*,12X,1P8E11.4)
(3478)      GO TO 100
(3479) 20     WRITE(KW,21) KBO,MB,((C(M,N),N=1,4),M=1,2)
(3480) 21     FORMAT (I3,I4,13X,1H*,4X,1P8E11.4)
(3481) 100    RETURN
(3482)      END

```

```

(3483)      SUBROUTINE ROTATE(N1)
(3484)      COMMON/BMAT/XLX(60,120),YLX(60,120),ZLX(60,120),
(3485)      +XHALF(20,40),YHALF(20,40),ZHALF(20,40),QHALF(20,40)
(3486)      COMMON/BINV/XIN(60,122),XOU(60,122),DLX(2),IROW(61),ICOL(61)
(3487)      DO 10 I=1,N1
(3488)      L = N1+I
(3489)      DO 10 J=1,N1
(3490)      M = N1+J
(3491)      J2 = 2*J
(3492)      J1 = J2-1
(3493)      M2 = 2*M
(3494)      M1 = M2-1
(3495)      ALX1 = 0.5*(XLX(I,J1)+XLX(L,M1))
(3496)      ALX2 = 0.5*(XLX(I,J2)+XLX(L,M2))
(3497)      BLX1 = -0.5*(XLX(L,J2)-XLX(I,M2))
(3498)      BLX2 = 0.5*(XLX(L,J1)-XLX(I,M1))
(3499)      CLX1 = ALX1-XLX(L,M1)
(3500)      CLX2 = ALX2-XLX(L,M2)
(3501)      DLX1 = BLX1-XLX(I,M2)
(3502)      DLX2 = BLX2+XLX(I,M1)
(3503)      YLX(I,J1) = ALX1+BLX1
(3504)      YLX(I,J2) = ALX2+BLX2
(3505)      YLX(I,M1) = CLX1+DLX1
(3506)      YLX(I,M2) = CLX2+DLX2
(3507)      YLX(L,J1) = CLX1-DLX1
(3508)      YLX(L,J2) = CLX2-DLX2
(3509)      YLX(L,M1) = ALX1-BLX1
(3510)      YLX(L,M2) = ALX2-BLX2
(3511)      RETURN
(3512)      END

```

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(3513)      SUBROUTINE ORBTAB(KW,N,M,K,SP,FR,A,B,S,P,POSIT,IPN)
(3514)      DIMENSION M(1),K(1),A(1),B(1),S(1),P(1)
(3515)      DIMENSION POSIT(76)
(3516)      IF(IPN.EQ.1) WRITE(KW,10) SP,FR
(3517) 10    FORMAT(//,1X,14HRESPONSE ORBIT/19H ROTATIONAL SPEED =.1PE11 4,
(3518) +4H RPM,6X,11HFREQUENCY =,1PE11 4,3H HZ//)
(3519)      WRITE(KW,101)
(3520) 101   FORMAT(33X,42H** PRINCIPAL RADII ** INCLINATION  PHASE/
(3521) +31H NO. STN LOCATION DISPL SLOPE,5X,
(3522) +5HMAJOR,6X,5HMINOR,7X,5H(DEG),4X,9HREFERENCE,4X,11HELLIPTICITY)
(3523)      LO = 0
(3524)      DO 60 I=1,N
(3525)      ELP=(A(I)+B(I))/(A(I)-B(I))
(3526)      IF(ELP.GT.1.0) ELP=1.0/ELP
(3527)      IG=M(I)
(3528)      LF = K(I)-2
(3529)      GO TO (20,30,20,30,40,40),LF
(3530) 100   WRITE (KW,11) K(I),M(I)
(3531) 11    FORMAT (/33H ERROR MESSAGE *** VALUE OF K8 (,13,17H AT STATION
(3532) +13,35H IS ILLEGAL. COMPUTATION IS HALTED )
(3533)      CALL EXIT
(3534) 20    WRITE(KW,21) I,M(I),POSIT(IG),A(I),B(I),S(I),P(I),ELP
(3535) 21    FORMAT(13,14,F10.4,5X,1H*,9X,2(1X,1P2E11 4),2X,1PE12 4)
(3536)      GO TO 60
(3537) 30    WRITE(KW,31) I,M(I),POSIT(IG),A(I),B(I),S(I),P(I),ELP
(3538) 31    FORMAT(13,14,F10.4,5X,1H*,9X,2(1X,1P2E11 4),2X,1PE12 4)
(3539)      GO TO 60
(3540) 40    LO = LO+1
(3541)      GO TO (20,50),LO
(3542)      GO TO 100
(3543) 50    LO = 0
(3544)      GO TO 30
(3545) 60    CONTINUE
(3546)      RETURN
(3547)      END

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(3548)      SUBROUTINE XCITAB(KW,IT,NO,M,K,PLX)
(3549)      DIMENSION PLX(1)
(3550)      DIMENSION M(1),K(1)
(3551)      WRITE (KW,10)
(3552)  10    FORMAT (///16H EXCITATION DATA)
(3553)      IF (IT.NE.0) GO TO 20
(3554)  100   WRITE (KW,11)
(3555)  11    FORMAT(/9X,4(1H*),6H TYPE ,4(1H*),2X,5(1H*),9H FORWARD ,2(1X,5(
(3556)      +1H*),1X),8HBACKWARD,1X,5(1H*))
(3557)      GO TO 25
(3558)  20    WRITE (KW,21)
(3559)  21    FORMAT(/9X,4(1H*),6H TYPE ,4(1H*),2X,5(1H*),10H VERTICAL ,5(1H*
(3560)      +),2X,4(1H*),12H HORIZONTAL ,4(1H*))
(3561)  25    WRITE (KW,26)
(3562)  26    FORMAT (23H NO. STN FORCE MOMENT,2(3X,8HIN-PHASE,6X,5HLAG ))
(3563)      LO = 0
(3564)      DO 70 I=1,NO
(3565)      I2 = 2*I
(3566)      I1 = I2-1
(3567)      L = NO+I
(3568)      L2 = 2*L
(3569)      L1 = L2-1
(3570)      LF = K(I)-2
(3571)      GO TO (40,50,40,50,60,60), LF
(3572)  200   WRITE (KW,31) K(I),M(I)
(3573)  31    FORMAT (/33H ERROR MESSAGE **** VALUE OF KB (,I3,I3H) AT STATION
(3574)      +I3,35H IS ILLEGAL. COMPUTATION IS HALTED )
(3575)      CALL EXIT
(3576)  40    WRITE (KW,41) I,M(I),PLX(I1),PLX(I2),PLX(L1),PLX(L2)
(3577)  41    FORMAT (I3,I4,5X,1H*,12X,1P4E11.4)
(3578)      GO TO 70
(3579)  50    WRITE (KW,51) I,M(I),PLX(I1),PLX(I2),PLX(L1),PLX(L2)
(3580)  51    FORMAT (I3,I4,12X,1H*,5X,1P4E11.4)
(3581)      GO TO 70
(3582)  60    LO = LO+1
(3583)      GO TO (40,65), LO
(3584)      GO TO 200
(3585)  65    LO = 0
(3586)      GO TO 50
(3587)  70    CONTINUE
(3588)      RETURN
(3589)      END

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(3590)      SUBROUTINE ORBIT(IT,B,S,T,P,ULX1,ULX2,V LX1,V LX2)
(3591)      R = 57.29578
(3592)      IF (IT.EQ.0) GO TO 1
(3593)      RLX1 = 0.5*ULX1
(3594)      RLX2 = 0.5*ULX2
(3595)      BLX1 = -0.5*V LX2
(3596)      BLX2 = 0.5*V LX1
(3597)      ALX1 = RLX1+BLX1
(3598)      ALX2 = RLX2+BLX2
(3599)      BLX1 = RLX1-BLX1
(3600)      BLX2 = RLX2-BLX2
(3601)      GO TO 10
(3602)  1      ALX1 = ULX1
(3603)          ALX2 = ULX2
(3604)          BLX1 = V LX1
(3605)          BLX2 = V LX2
(3606)  10      F = SQRT(ALX1*ALX1+ALX2*ALX2)
(3607)          B2 = BLX1*BLX1+BLX2*BLX2
(3608)          G = SQRT(B2)
(3609)          B = F+G
(3610)          S = F-G
(3611)          F = F/B
(3612)          G = G/B
(3613)          RLX1 = (ALX1*BLX1+ALX2*BLX2)/B2
(3614)          RLX2 = (ALX2*BLX1-ALX1*BLX2)/B2
(3615)          T = 0.5*R*ATAN2(RLX2,RLX1)
(3616)  20      X = ALX1+BLX1
(3617)          Y = ALX2-BLX2
(3618)          P = R*ATAN2(Y,X)
(3619)      RETURN
(3620)      END

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(3621)      SUBROUTINE ASNTAB(K,NF,IW,F,D,IS)
(3622)      DIMENSION IW(2,1),F(1),D(2,1)
(3623)      DO 50 I = 1,NF
(3624)      L = IW(1,I)
(3625)      M = L+IW(2,I)
(3626)      IF (L.EQ.1) GO TO 10
(3627)      IF (M.EQ.1) GO TO 20
(3628)      IF (IS.EQ.1) GO TO 5
(3629)      WRITE (K,100) F(I),(D(J,I),J=1,2)
(3630)      GO TO 50
(3631)  5    WRITE (K,100) F(I),D(2,I)
(3632)      GO TO 50
(3633)  10   WRITE (K,200) F(I),(D(J,I),J=1,2)
(3634)      GO TO 50
(3635)  20   IF (M.EQ.2) GO TO 30
(3636)      WRITE (K,300) F(I),(D(J,I),J=1,2)
(3637)      GO TO 50
(3638)  30   WRITE (K,400) F(I),(D(J,I),J=1,2)
(3639)  50   CONTINUE
(3640)  100  FORMAT (1PE11.4,2(5X,E11.4))
(3641)  200  FORMAT (1PE11.4,2(5X,E11.4),5X,34HFORWARD WHIRL MOTION IS DEGENERA
(3642)      +TE)
(3643)  300  FORMAT (1PE11.4,2(5X,E11.4),5X,35HBACKWARD WHIRL MOTION IS DEGENER
(3644)      +ATE)
(3645)  400  FORMAT (1PE11.4,2(5X,E11.4),5X,33HBOTH WHIRL MOTIONS ARE DEGENERAT
(3646)      +E)
(3647)      RETURN
(3648)      END

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(3649)      SUBROUTINE SYNTAB(K,NS,IW,S,D,ISO)
(3650)      C
(3651)      C      DOUBLE PRECISION REAL ALGEBRA VERSION      OCT 3, 1979
(3652)      C
(3653)      DIMENSION IW(2,1),S(1),D(2,1)
(3654)      JSO=ISO+1
(3655)      DO 30 I=1,NS
(3656)      RPM = 60.0*S(I)
(3657)      L = IW(1,I)
(3658)      IF (L.EQ.1) GO TO 10
(3659)      WRITE(K,100) RPM,D(JSO,I)
(3660)      GO TO 30
(3661)  10    WRITE(K,200) RPM,D(JSO,I)
(3662)  30    CONTINUE
(3663)      RETURN
(3664)  100   FORMAT (1PE11.4,5X,E11.4)
(3665)  200   FORMAT (1PE11.4,5X,E11.4,5X,27HFORWARD WHIRL IS DEGENERATE)
(3666)      END

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(3667)      SUBROUTINE INVC (N,IERR)
(3668)      C
(3669)      C      INVERSION OF COMPLEX MATRIY
(3670)      C      XOU = INVERSE OF XIN
(3671)      C      ORIGINAL XIN IS DESTROYED
(3672)      C      N = RANK OF SYSTEM
(3673)      C      IERR = ERROR FLAG, RETURNED AS -1 IF XIN IS SINGULAR
(3674)      C      IROW = INTEGER ARRAY
(3675)      C      ICOL = INTEGER ARRAY
(3676)      C      DLX = COMPLEX DETERMINANT OF D
(3677)      C
(3678)      C      XOU,XIN,IROW,ICOL,DLX ARE ASSIGNED IN LABELED COMMON/BINV/
(3679)      C
(3680)      COMMON/BINV/XIN(60,122),XOU(60,122),DLX(2),IROW(61),ICOL(61)
(3681)      IERR = 0
(3682)      DLX(1) = 1.0
(3683)      DLX(2) = 0.0
(3684)      N2 = 2*N
(3685)      DO 100 I=1,N
(3686)      DO 100 J=1,N2
(3687) 100    XOU(I,J) = XIN(I,J)
(3688)      M = N+1
(3689)      M2 = 2*M
(3690)      M1 = M2-1
(3691)      DO 110 I=1,N
(3692)      IROW(I) = I
(3693) 110    ICOL(I) = I
(3694)      DO 250 K=1,N
(3695)      K2 = 2*K
(3696)      K1 = K2-1
(3697)      AREA = XOU(K,K1)
(3698)      AIMA = XOU(K,K2)
(3699)      AMAX = AREA*AREA+AIMA*AIMA
(3700)      IC=K
(3701)      JC=K
(3702)      JC2 = K2
(3703)      JC1 = K1
(3704)      DO 130 I=K,N
(3705)      DO 130 J=K,N
(3706)      J2 = 2*J
(3707)      J1 = J2-1
(3708)      BREA = XOU(I,J1)
(3709)      BIMA = XOU(I,J2)
(3710)      BMAX = BREA*BREA+BIMA*BIMA
(3711)      IF(BMAX-AMAX) 130,120,120
(3712) 120    AMAX = BMAX
(3713)      IC = I
(3714)      JC = J
(3715)      JC2 = J2
(3716)      JC1 = J1
(3717) 130    CONTINUE
(3718)      IF (K.EQ.IC) GO TO 131
(3719)      KI = ICOL(K)
(3720)      ICOL(K) = ICOL(IC)

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(3721)      ICOL(IC) = KI
(3722) 131   IF (K EQ JC) GO TO 134
(3723)      KI = IROW(K)
(3724)      IROW(K) = IROW(JC)
(3725)      IROW(JC) = KI
(3726) 134   IF (AMAX) 150,140,150
(3727) 140   IERR = -1
(3728)      GO TO 320
(3729) 150   DO 160 J=1,N
(3730)      J2 = 2*J
(3731)      J1 = J2-1
(3732)      E1 = XOU(K,J1)
(3733)      E2 = XOU(K,J2)
(3734)      XOU(K,J1) = XOU(IC,J1)
(3735)      XOU(K,J2) = XOU(IC,J2)
(3736)      XOU(IC,J1) = E1
(3737) 160   XOU(IC,J2) = E2
(3738)      DO 170 I=1,N
(3739)      E1 = XOU(I,K1)
(3740)      E2 = XOU(I,K2)
(3741)      XOU(I,K1) = XOU(I,JC1)
(3742)      XOU(I,K2) = XOU(I,JC2)
(3743)      XOU(I,JC1) = E1
(3744) 170   XOU(I,JC2) = E2
(3745)      DO 200 I=1,N
(3746)      IF (I-K) 190,180,190
(3747) 180   XOU(I,M1) = 1.0
(3748)      XOU(I,M2) = 0.0
(3749)      GO TO 200
(3750) 190   XOU(I,M1) = 0.0
(3751)      XOU(I,M2) = 0.0
(3752) 200   CONTINUE
(3753)      PVT = XOU(K,K1)
(3754)      QVT = XOU(K,K2)
(3755)      U = PVT
(3756)      V = QVT
(3757)      IF (K EQ IC.AND.K.EQ.JC.OR K.NE IC.AND K.NE.JC) GO TO 205
(3758)      U = -U
(3759)      V = -V
(3760) 205   W = U*U+V*V
(3761)      PVT = PVT/W
(3762)      QVT = -QVT/W
(3763)      U1 = DLX(1)*U-DLX(2)*V
(3764)      U2 = DLX(1)*V+DLX(2)*U
(3765)      DLX(1) = U1
(3766)      DLX(2) = U2
(3767)      DO 210 J=1,M
(3768)      J2 = 2*J
(3769)      J1 = J2-1
(3770)      AREA = XOU(K,J1)
(3771)      AIMA = XOU(K,J2)
(3772)      XOU(K,J1) = AREA*PVT-AIMA*QVT
(3773) 210   XOU(K,J2) = AREA*QVT+AIMA*PVT
(3774)      DO 240 I=1,N

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(3775)      IF(I-K) 220,240,220
(3776) 220   BREA = XOU(I,K1)
(3777)      BIMA = XOU(I,K2)
(3778)      DO 230 J=1,M
(3779)      J2 = 2*J
(3780)      J1 = J2-1
(3781)      XOU(I,J1) = XOU(I,J1)-BREA*XOU(K,J1)+BIMA*XOU(K,J2)
(3782) 230   XU(I,J2) = XOU(I,J2)-BREA*XOU(K,J2)-BIMA*XOU(K,J1)
(3783) 240   CONTINUE
(3784)      DO 250 I=1,N
(3785)      XOU(I,K1) = XOU(I,M1)
(3786) 250   XOU(I,K2) = XOU(I,M2)
(3787)      DO 280 I=1,N
(3788)      DO 260 L=1,N
(3789)      IF(IROW(I)-L) 260,270,260
(3790)      CONTINUE
(3791) 270   DO 280 J=1,M2
(3792) 280   XIN(L,J) = XOU(I,J)
(3793)      DO 310 J=1,N
(3794)      J2 = 2*J
(3795)      J1 = J2-1
(3796)      DO 290 L=1,N
(3797)      L2 = 2*L
(3798)      L1 = L2-1
(3799)      IF(ICOL(J)-L) 290,300,290
(3800) 290   CONTINUE
(3801) 300   DO 310 I=1,N
(3802)      XOU(I,L1) = XIN(I,J1)
(3803) 310   XOU(I,L2) = XIN(I,J2)
(3804) 320   RETURN
(3805)      END

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(3806)      SUBROUTINE MOUTC (A,L,M,NRA,IR,IC,IRLAB,ICLAB,LINE,KW)
(3807) C      A IS COMPLEX ARRAY
(3808) C      REAL PARTS ARE IN ODD COLUMNS
(3809) C      IMAGINARY PARTS ARE IN EVEN COLUMNS
(3810) C      IR IS ARRAY OF INDICES FOR ROW (USED WHEN IR=1)
(3811) C      IC IS ARRAY OF INDICES FOR COL (USED WHEN IC=1)
(3812) C      NRA IS DIMENSIONED NO OF ROWS IN A
(3813) C      OUTPUT FORM RE,IM      X XXXE XX,  X XXXE XX
(3814) C      LINE IS LINE NO ON PAGE OF FIRST OUT-PUT LINE
(3815)      DIMENSION A(NRA,1)
(3816)      DIMENSION IRLAB(1),ICLAB(1)
(3817)      IC1 = 1
(3818)      IA1 = 1
(3819)      IC2 = MINO(5,M)
(3820)      IA2 = 2*IC2
(3821)      LINE=LINE+2
(3822) 100    IL1 = 1
(3823)      IL2 = MINO (58-LINE,L)
(3824)      IF (IL2.NE L) GO TO 195
(3825) 110    IF (IC.EQ 1) GO TO 120
(3826)      WRITE (KW,130) (I,I=IC1,IC2)
(3827)      GO TO 140
(3828) 120    WRITE (KW,130) (ICLAB(I),I=IC1,IC2)
(3829) 130    FORMAT (/ I23,4I24/)
(3830) 140    DO 170 I=IL1,IL2
(3831)      IF (IR.EQ.1) GO TO 150
(3832)      WRITE (KW,160) I,(A(I,J),J=IA1,IA2)
(3833)      GO TO 170
(3834) 150    WRITE (KW,160) IRLAB(I),(A(I,J),J=IA1,IA2)
(3835) 160    FORMAT (I6,4X,1P5(E12.3,1H,,E11.3))
(3836) 170    CONTINUE
(3837)      IF (I.GE.L) GO TO 190
(3838)      IL1 = IL2+1
(3839)      IL2 = MINO (IL2+58,L)
(3840)      WRITE (KW,180)
(3841) 180    FORMAT(/)
(3842)      GO TO 110
(3843) 190    IF (IC2.GE.M) GO TO 200
(3844)      IC1 = IC2+1
(3845)      IA1 = IA2+1
(3846)      IC2 = MINO (IC2+5,M)
(3847)      IA2 = 2*IC2
(3848)      LINE=LINE+2
(3849)      GO TO 100
(3850) 195    WRITE (KW,185)
(3851) 185    FORMAT(1H1)
(3852)      LINE=0
(3853)      GO TO 100
(3854) 200    RETURN
(3855)      END

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(3856) SUBROUTINE KRAUTE(NF,NB,KS,KE,KW,IT,IS,F,Y,IRUN,TABLX,PLX,WLX,
(3857) +BIG,SMALL,SLANT,PHASE,JDG)
(3858) DIMENSION TABLX(60,1),PLX(1),WLX(1)
(3859) DIMENSION ALX(22),AOLX(22),AA2LX(22),DOLX(20),D1LX(2,22),ULX(22),
(3860) +Y1LX(22),ZZLX(6),DETLX(2,22)
(3861) DIMENSION F(1),Y(1),M8(20),K8(20),BIG(1),SMALL(1)
(3862) DIMENSION X(40,40),POSIT(76),RET(11),XINT(11)
(3863) DIMENSION A1(10,10),B1(10,10),AC5(10),AM8(10),AM9(10),B(10),EO(10)
(3864) +,Q2(11),Z1(3,10),Z2(3,10),FSR(11),SLANT(1),PHASE(1),AM7(10)
(3865) DIMENSION IRLAB(40),ICLAB(40)
(3866) COMMON/BMAT/XLX(60,120),YLX(60,120),ZLX(60,120)
(3867) +XHALF(20,40),YHALF(20,40),ZHALF(20,40),QHALF(20,40)
(3868) COMMON/BINV/XIN(60,122),XOU(60,122),DLX(2),IROW(61),ICOL(61)
(3869) COMMON/WUS/M8,K8,X,POSIT
(3870) COMMON/CODA/K9(20)
(3871) COMMON/WUSA/RET,XINT
(3872) COMMON/XGCON/SLOW,RLAX,IGEN
(3873) COMMON/WR/LW,LR
(3874) COMMON/CBEG/IBEG
(3875) LINE = 0
(3876) N40 = 40
(3877) M6=60
(3878) JR=1
(3879) IF (IGEN) 1,810,2
(3880) 1 K5MAX = -IGEN
(3881) GO TO 3
(3882) 2 K5MAX = IGEN
(3883) 3 CONTINUE
(3884) C CREATE MATRIX INTERPOLATION FILE
(3885) MF = NF-1
(3886) MF2 = 2*MF
(3887) N1 = 1
(3888) N2 = NB
(3889) N10 = N1+NB
(3890) N20 = N2+NB
(3891) N202 = 2*N20
(3892) ISP = -1
(3893) 10 DO 60 I=N1,N2
(3894) DO 30 J=1,N2
(3895) J2 = 2*J
(3896) J1 = J2-1
(3897) REWIND KS
(3898) DO 15 K=1,NF
(3899) K2 = 2*K
(3900) K1 = K2-1
(3901) FSR(K)=6.283185307**2*(F(K)*F(K))
(3902) READ (KS) SPD,FRE,((YLX(IA,JA),JA=1,N202),IA=1,N20)
(3903) IF((FRE-F(K)).LE.1.E-5) GO TO 14
(3904) WRITE(KW,1000) K
(3905) 1000 FORMAT(44HIF FAULTY DATA IN FILE (KS) AT FREQUENCY POINT,I3)
(3906) REWIND KS
(3907) REWIND KE
(3908) CALL EXIT
(3909) 14 IF(IRUN.EQ. 2 OR. IRUN EQ 4) READ (KS) (PLX(IA),IA=1,N202)

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(3910)      ULX(K1) = YLX(I,J1)
(3911) 15    ULX(K2) = YLX(I,J2)
(3912)      DO 20 K=1,NF
(3913)      K1 = 2*K-1
(3914) 20    Y(K) = ULX(K1)
(3915)      CALL SPLINE(ISP,NF,RET,XINT,F,Y,Z1,KW,IER)
(3916)      IF (IER.NE.0) GO TO 806
(3917)      DO 25 K=1,NF
(3918)      K2 = 2*K
(3919) 25    Y(K) = ULX(K2)
(3920)      IER = 0
(3921)      CALL SPLINE(ISP,NF,RET,XINT,F,Y,Z2,KW,IER)
(3922)      IF (IER.NE.0) GO TO 806
(3923)      WRITE (KE) ((ULX(K),K=1,MF2),((Z1(IA,K),Z2(IA,K)),IA=1,3),K=1,MF)
(3924) 30    CONTINUE
(3925)      IF (IS.EQ.0) GO TO 60
(3926)      REWIND KS
(3927)      DO 45 K=1,NF
(3928)      K2 = 2*K
(3929)      K1 = K2-1
(3930)      READ (KS) SPD,FRE,((YLX(IA,JA),JA=1,N202),IA=1,N20)
(3931)      IF((FRE-F(K)).LE.1.E-3) GO TO 34
(3932)      WRITE(KW,1000) K
(3933)      REWIND KS
(3934)      REWIND KE
(3935)      CALL EXIT
(3936) 34    IF(IRUN.EQ.2 .OR. IRUN.EQ.4) READ (KS) (PLX(IA),IA=1,N202)
(3937)      IF (N1.EQ.1) GO TO 40
(3938)      J = I-NB
(3939)      GO TO 42
(3940) 40    J = I+NB
(3941) 42    J2 = 2*J
(3942)      J1 = J2-1
(3943)      ULX(K1) = YLX(I,J1)
(3944) 45    ULX(K2) = YLX(I,J2)
(3945)      DO 50 K=1,NF
(3946)      K1 = 2*K-1
(3947) 50    Y(K) = ULX(K1)
(3948)      IER = 0
(3949)      CALL SPLINE(ISP,NF,RET,XINT,F,Y,Z1,KW,IER)
(3950)      IF (IER.NE.0) GO TO 806
(3951)      DO 55 K=1,NF
(3952)      K2 = 2*K
(3953) 55    Y(K) = ULX(K2)
(3954)      IER = 0
(3955)      CALL SPLINE(ISP,NF,RET,XINT,F,Y,Z2,KW,IER)
(3956)      IF (IER.NE.0) GO TO 806
(3957)      WRITE (KE) ((ULX(K),K=1,MF2),((Z1(IA,K),Z2(IA,K)),IA=1,3),K=1,MF)
(3958) 60    CONTINUE
(3959)      IF (N1.EQ.N10) GO TO 65
(3960)      N1 = N10
(3961)      N2 = N20
(3962)      GO TO 10
(3963) 65    IROT = 1+IS

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(3964) C      BEGIN ITERATION FOR EIGENVALUE
(3965) C      K05M      NUMBER OF EIGEN ROOTS FOUND
(3966) C      K05      ROOT NUMBER BEING SOUGHT
(3967) 100     K05M = 0
(3968)         KBEG = 0
(3969)         JBEG = 0
(3970) 101     IF (IBEG.EQ.0.AND.JBEG.EQ.0) GO TO 105
(3971) 102     IF (KBEG.GE.K5MAX) GO TO 5001
(3972)         KBEG = KBEG+1
(3973)         IF (IBEG.EQ.0) GO TO 102
(3974)         KP19 = 1
(3975)         READ (LR,3000) P10,C5
(3976) 3000    FORMAT (2020.4)
(3977) 105     K05 = K05M+1
(3978)         K052 = 2*K05
(3979)         K051 = K052-1
(3980)         IDOWN = 0
(3981)         KDOWN = 0
(3982)         RESOLD = 0.0
(3983)         P7 = 0.
(3984)         KP9 = 0
(3985)         IF (IBEG.NE.0) GO TO 120
(3986)         C5 = 0
(3987)         KP19=0
(3988) C      COMPUTE DETERMINANTS AT CONTROL FREQUENCIES
(3989) 120     CONTINUE
(3990)         REWIND KS
(3991)         K = 0
(3992) 121     K=K+1
(3993)         K2 = 2*K
(3994)         K1 = K2-1
(3995)         READ (KS) SPD,FRE,((YLX(I,J),J=1,N202),I=1,N202)
(3996)         IF (IRUN.EQ.2.OR.IRUN.EQ.4) READ(KS)(PLX(IQ),IQ=1,N202)
(3997)         C5K = C5/F(K)
(3998)         DO 160 L=1,2
(3999)             IF (IS.EQ.1) GO TO 130
(4000)             IF (IROT.NE.L) GO TO 160
(4001) 130     MB = (L-1)*NB
(4002)             LB = (2*L-3)*NB
(4003)             DO 140 I=1,NB
(4004)                 IO = I+MB
(4005)                 I2 = I+NB
(4006)                 DO 135 J=1,NB
(4007)                     JO = J+MB
(4008)                     J02 = 2*JO
(4009)                     J01 = J02-1
(4010)                     J1 = JO-LB
(4011)                     J12 = 2*J1
(4012)                     J11 = J12-1
(4013)                     TABLX(IO,J01) = YLX(IO,J01)/FSQ(K)
(4014)                     TABLX(IO,J02) = YLX(IO,J02)/FSQ(K)
(4015)                     IF (I.EQ.J) TABLX(IO,J02) = TABLX(IO,J02)-C5K
(4016)                     IF (IS.EQ.0) GO TO 135
(4017)                     TABLX(IO,J11)=YLX(IO,J11)/FSQ(K)

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(4018)          TABLX(I0,J12)=YLX(I0,J12)/FSQ(K)
(4019) 135      CONTINUE
(4020) 140      CONTINUE
(4021) 160      CONTINUE
(4022)          IPID = 0
(4023)          CALL PINVC(IPID,KW,NB,N40,N40,IS,IROT,TABLX,JDG)
(4024) C        FACTORIZATION OF KNOWN EIGENVALUES
(4025)          IF (K05.EQ 1) GO TO 205
(4026)          K17 = 0
(4027)          A4LX1 = 0.0
(4028)          A4LX2 = 0.0
(4029)          A1LX1 = 1.0
(4030)          A1LX2 = 0.0
(4031)          DO 195 K07=1,K05M
(4032)            K072 =2*K07
(4033)            K071 = K072-1
(4034)            Q = Q2(K07)
(4035)            XQ = F(K)*F(K)
(4036)            U = AM8(K07)
(4037)            SIZEB = E0(K07)/XQ
(4038)            AX = SIZEB-U
(4039)            AY = AM7(K07)/XQ-C5/F(K)
(4040)            SIZEA = AX*AX+AY*AY
(4041)            SIZEB = SIZEB*SIZEB*2.5D-08*RLAX
(4042)            IF (SIZEA GE SIZEB) GO TO 180
(4043)            WRITE (KW,1010) K07
(4044) 1010      FORMAT (/44H TRUNCATION UNCERTAINTY ENCOUNTERED AT ROOT ,I2,1H \
(4045)            K17 = K07
(4046)            A4LX1 = 0.0
(4047)            A4LX2 = 0.0
(4048)            A1LX1 = 1.0
(4049)            A1LX2 = 0.0
(4050)            DLX(1) =-Q*D1LX(1,K072)
(4051)            DLX(2) = Q*D1LX(1,K071)
(4052)            GO TO 195
(4053) 180      B2LX1 = AX
(4054)            B2LX2 = AY
(4055)            A1LX0 = A1LX1*B2LX1-A1LX2*B2LX2
(4056)            A1LX2 = A1LX1*B2LX2+A1LX2*B2LX1
(4057)            A1LX1 = A1LX0
(4058)            B2LX0 = B2LX1*B2LX1+B2LX2*B2LX2
(4059)            A4LX1 = A4LX1+B2LX2/B2LX0
(4060)            A4LX2 = A4LX2+B2LX1/B2LX0
(4061) 195      CONTINUE
(4062)            A1LX0 = A1LX1+A1LX1+A1LX2+A1LX2
(4063)            AOLX(K1) = A1LX1/A1LX0
(4064)            AOLX(K2) =-A1LX2/A1LX0
(4065)            AA2LX(K1) = A4LX1/F(K)
(4066)            AA2LX(K2) = A4LX2/F(K)
(4067)            DRE = AOLX(K1)*DLX(1)-AOLX(K2)*DLX(2)
(4068)            DIM = AOLX(K1)*DLX(2)+AOLX(K2)*DLX(1)
(4069)            DLX(1) = DRE
(4070)            DLX(2) = DIM
(4071) 205      DETLX(IROT,K1) = DLX(1)

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(4072)      DETLX(IROT,K2) = DLX(2)
(4073)      IF (K.LT.NF) GO TO 121
(4074)  C    DETERMINANT INTERPOLATION
(4075)      ISP = 1
(4076)      IF(KP19.EQ.1) GO TO 228
(4077)      IF (KBEG.EQ.0.AND.IBEG.EQ.-1) GO TO 228
(4078)      DO 226 K=1,NF
(4079)      K2 = 2*K
(4080)      K1 = K2-1
(4081)  226  Y(K) = ALOG10((DETLX(IROT,K1)**2+DETLX(IROT,K2)**2)*10.0+1.0)
(4082)      NI=100
(4083)      IER = 0
(4084)      CALL SPLINE(NI,NF,RET,XINT,F,Y,Z1,KW,IER)
(4085)      IF (IER.NE.0) GO TO 806
(4086)      IF(NI.EQ.1.AND.RET(1).GE.F(1).AND.RET(1).LE.F(NF)) GO TO 227
(4087)      P10 = SQRT(F(1)*F(NF))
(4088)      GO TO 228
(4089)  227  P10=RET(1)
(4090)  228  DO 230 K=1,NF
(4091)      K2 = 2*K
(4092)      K1 = K2-1
(4093)      Y1LX(K1) = DETLX(IROT,K1)
(4094)  230  Y(K) = Y1LX(K1)
(4095)      XINT(1) = P10
(4096)      IER = 0
(4097)      CALL SPLINE(ISP,NF,RET,XINT,F,Y,Z1,KW,IER)
(4098)      IF (IER.NE.0) GO TO 806
(4099)      P7 = RET(1)
(4100)      DO 235 K=1,NF
(4101)      K2 = 2*K
(4102)      Y1LX(K2) = DETLX(IROT,K2)
(4103)  235  Y(K) = Y1LX(K2)
(4104)      IER = 0
(4105)      CALL SPLINE(ISP,NF,RET,XINT,F,Y,Z2,KW,IER)
(4106)      IF (IER.NE.0) GO TO 806
(4107)      R4LX1 = P7
(4108)      R4LX2 = RET(1)
(4109)  C    LOCATE FREQUENCY INTERVAL
(4110)      KO=1
(4111)      DO 1115 IK=1,MF
(4112)      IF (P10.GE.F(IK)) GO TO 1115
(4113)      KO=IK-1
(4114)      GO TO 236
(4115)  1115  CONTINUE
(4116)      KO=MF
(4117)  236  DF=P10-F(KO)
(4118)      DO 240 K=1,3
(4119)      K2 = 2*K
(4120)      K1 = K2-1
(4121)      ZZLX(K1) = Z1(K,KO)
(4122)  240  ZZLX(K2) = Z2(K,KO)
(4123)      R5LX1 = ZZLX(1)
(4124)      R5LX2 = ZZLX(2)
(4125)      D0LX(K051) = 2.0*ZZLX(3)

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(4126)      DOLX(K052) = 2.0*ZZLX(4)
(4127)      IF (DF.EQ.0.) GO TO 241
(4128)      R5LX1 = R5LX1+DF*(2.0*ZZLX(3)+3.0*DF*ZZLX(5))
(4129)      R5LX2 = R5LX2+DF*(2.0*ZZLX(4)+3.0*DF*ZZLX(6))
(4130)      DOLX(K051) = DOLX(K051)+6.0*DF*ZZLX(5)
(4131)      DOLX(K052) = DOLX(K052)+6.0*DF*ZZLX(6)
(4132) 241   CONTINUE
(4133)      RESNEW = R4LX1**2+R4LX2**2
(4134)      IF (KP9.EQ.0) GO TO 243
(4135)      RESRAT = RESNEW/RESOLD
(4136)      IF (IDOWN.EQ.1) GO TO 242
(4137)      IF (RESNEW.LE.RESOLD) GO TO 243
(4138)      KDOWN = KDOWN+1
(4139)      IF (KDOWN.EQ.4) GO TO 393
(4140)      IDOWN = 1
(4141)      GO TO 243
(4142) 242   IF (RESNEW.LE.RESOLD) IDOWN = 0
(4143) 243   RESOLD = RESNEW
(4144)  C     COMPUTE C-DERIVATIVES OF DETERMINANTS AT CONTROL FREQUENCIES
(4145)      REWIND KS
(4146)      K = 0
(4147) 245   K = K+1
(4148)      K2=2*K
(4149)      K1=K2-1
(4150)      READ (KS) SPD,FRE,((YLX(I,J),J=1,N202),I=1,N20)
(4151)      IF (IRUH.EQ.2.OR.IRUH.EQ.4) READ(KS) (PLX(IQ),IQ=1,N202)
(4152)      P5RE = 0.0
(4153)      P5IM = 0.0
(4154)      C5K = C5/F(K)
(4155)      X1 = 1./F(K)
(4156)      DO 330 N=1,2
(4157)      IF (IS.EQ.1) GO TO 252
(4158)      IF (IROT.NE.N) GO TO 330
(4159) 252   MA=(N-1)*NB
(4160)      DO 325 M=1,NB
(4161)      MX=M+MA
(4162)      MX2 = 2*MX
(4163)      MX1 = MX2-1
(4164)      DO 310 L=1,2
(4165)      IF (IS.EQ.1) GO TO 255
(4166)      IF (IROT.NE.L) GO TO 310
(4167) 255   MB = (L-1)*NB
(4168)      LB = (3-2*L)*NB
(4169)      DO 280 I=1,NB
(4170)      IO = I+MB
(4171)      I2 = I+NB
(4172)      DO 275 J=1,NB
(4173)      JO = J+MB
(4174)      JO2 = 2*JO
(4175)      JO1 = JO2-1
(4176)      J1 = JO+LB
(4177)      J12 = 2*J1
(4178)      J11 = J12-1
(4179)      IF (I.EQ.J) GO TO 265

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(4180)      TABLX(IO,J01) = YLX(IO,J01)/FSQ(K)
(4181)      TABLX(IO,J02) = YLX(IO,J02)/FSQ(K)
(4182)      IF (IS.EQ.0) GO TO 275
(4183)      TABLX(IO,J11) = 0.0
(4184)      TABLX(IO,J12) = 0.0
(4185)      GO TO 275
(4186) 265   IF (N.NE.L.OR.I.NE.M) GO TO 270
(4187)      TABLX(IO,J01) = 1.0
(4188)      TABLX(IO,J02) = 0.0
(4189)      GO TO 272
(4190) 270   TABLX(IO,J01) = YLX(IO,J01)/FSQ(K)
(4191)      TABLX(IO,J02) = YLX(IO,J02)/FSQ(K)-C5K
(4192) 272   IF (IS.EQ.0) GO TO 275
(4193)      TABLX(IO,J11) = YLX(IO,J11)/FSQ(K)
(4194)      TABLX(IO,J12) = YLX(IO,J12)/FSQ(K)
(4195) 275   CONTINUE
(4196) 280   CONTINUE
(4197) 310   CONTINUE
(4198)      IPID = 0
(4199)      CALL PINVC(IPID,KW,NB,N40,N40,IS,IROT,TABLX,JDG)
(4200)      P5RE = P5RE+DLX(1)
(4201)      P5IM = P5IM+DLX(2)
(4202)      TABLX(MX,MX1) = 0.0
(4203)      TABLX(MX,MX2) = 0.0
(4204)      IPID = 0
(4205)      CALL PINVC(IPID,KW,NB,N40,N40,IS,IROT,TABLX,JDG)
(4206)      P5RE = P5RE-DLX(1)
(4207)      P5IM = P5IM-DLX(2)
(4208) 325   CONTINUE
(4209) 330   CONTINUE
(4210)      DLX(1) = X1*P5IM
(4211)      DLX(2) = -X1*P5RE
(4212)  C    FACTORIZATION OF KNOWN EIGENVALUES
(4213)      IF (K05.EQ.1) GO TO 340
(4214)      IF (K17.EQ.0) GO TO 335
(4215)      Q = Q2(K17)
(4216)      DLX(1) = (R5LX1-R4LX1/Q)/Q
(4217)      DLX(2) = (R5LX2-R4LX2/Q)/Q
(4218)      K172 = 2*K17
(4219)      K171 = K172-1
(4220)      DLX(1) = DLX(1)+D1LX(2,K172)
(4221)      DLX(2) = DLX(2)-D1LX(2,K171)
(4222)      CONST = 2.0*AM8(K17)/Q
(4223)      DRE = DLX(2)/CONST
(4224)      DIM = -DLX(1)/CONST
(4225)      DLX(1) = AOLX(K1)*DRE-AOLX(K2)*DIM+AA2LX(K1)*Y1LX(K1)
(4226)      +      -AA2LX(K2)*Y1LX(K2)
(4227) 335   DLX(2) = AOLX(K1)*DIM+AOLX(K2)*DRE+AA2LX(K1)*Y1LX(K2)
(4228)      +      +AA2LX(K2)*Y1LX(K1)
(4229) 340   Y1LX(K1) = DLX(1)
(4230)      Y1LX(K2) = DLX(2)
(4231)      IF (K.LT.NF) GO TO 245
(4232)  C    C-DERIVATIVE INTERPOLATION
(4233)      DO 345 K=1,NF

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(4234)      K1 = 2*K-1
(4235) 345   Y(K) = Y1LX(K1)
(4236)      XINT(1)=P10
(4237)      IER = 0
(4238)      CALL SPLINE(ISP,NF,RET,XINT,F,Y,Z1,KW,IER)
(4239)      IF (IER.NE.0) GO TO 806
(4240)      R6 = RET(1)
(4241)      DO 350 K=1,NF
(4242)      K2 = 2*K
(4243) 350   Y(K) = Y1LX(K2)
(4244)      IER = 0
(4245)      CALL SPLINE(ISP,NF,RET,XINT,F,Y,Z2,KW,IER)
(4246)      IF (IER.NE.0) GO TO 806
(4247)      D1LX(1,K051) = R6
(4248)      D1LX(1,K052) = RET(1)
(4249)      DO 355 K=1,3
(4250)      K2 = 2*K
(4251)      K1 = K2-1
(4252)      ZZLX(K1) = Z1(K,K0)
(4253) 355   ZZLX(K2) = Z2(K,K0)
(4254)      IF (DF.EQ.0.) GO TO 356
(4255)      ZZLX(1) = ZZLX(1)+DF*(2.0*ZZLX(3)+3.0*DF*ZZLX(5))
(4256)      ZZLX(2) = ZZLX(2)+DF*(2.0*ZZLX(4)+3.0*DF*ZZLX(6))
(4257) 356   D1LX(2,K051) = ZZLX(1)
(4258)      D1LX(2,K052) = ZZLX(2)
(4259) C     ESTIMATE RESIDUE
(4260)      D1LX0 = D1LX(1,K051)**2+D1LX(1,K052)**2
(4261)      DLX(1) = (R4LX1*D1LX(1,K051)+R4LX2*D1LX(1,K052))/D1LX0
(4262)      DLX(2) = (R4LX2*D1LX(1,K051)-R4LX1*D1LX(1,K052))/D1LX0
(4263)      WNUV1 = (R5LX1*D1LX(1,K051)+R5LX2*D1LX(1,K052))/D1LX0
(4264)      WNUV2 = (R5LX2*D1LX(1,K051)-R5LX1*D1LX(1,K052))/D1LX0
(4265)      P8 = -DLX(2)/WNUV2
(4266)      C9 = -DLX(1)-WNUV1*P8
(4267)      E1 = (P8*P8+C9*C9)/(P10*P10+C5*C5)
(4268)      KP9 = KP9+1
(4269)      IF (ABS(C9).GE.100.0.AND.E1.GT.1.0E-03) C9=C9*0.01
(4270)      E1 = E1/RLAX
(4271)      Q3=P10
(4272)      KP19=0
(4273)      Q2(K05) = P10
(4274)      AC5(K05) = C5
(4275)      AM8(K05) = -WNUV2/2.0
(4276)      ED(K05) = AM8(K05)*P10*P10
(4277)      AM7(K05) = (P10*WNUV1+C5)*P10/2.0
(4278)      IF (ABS(WNUV2).LT.1.0E-20) GO TO 364
(4279)      B(K05) = -C5/WNUV2/P10
(4280)      AM9(K05) = (C5/P10-WNUV1)/WNUV2/2.0
(4281) 364   IF (IGEN.GE.0.OR.KP9.NE.1) GO TO 3641
(4282)      WRITE(KW,1091)
(4283) 1091  FORMAT(1H1)
(4284)      WRITE (KW,1060)
(4285) 1060  FORMAT (/49H I      FREQ      DAMP      MODAL MASS DAMP RATIO
(4286)      +41HF-CHANGE      C-CHANGE      RESIDUE      D CHECK)
(4287) 3641  IF (IGEN.LT.0) WRITE (KW,1061) KP9,P10,C5,AM8(K05),2(K05),

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(4288)      +P8,C9,RESOLD,AM9(K05)
(4289) 1061  FORMAT (I3,1P9D11.3)
(4290)      IF(E1.GT.1 DE-12.OR.RESRAT GT 1.0E-02) GO TO 365
(4291)      K05M = K05
(4292)      GO TO 395
(4293) C     TWO-PARAMETER NEWTON-RAPHSON ITERATION
(4294) 365   IF (KP9.GE.20) GO TO 394
(4295)      PNEW = P10+P8
(4296)      P10=PNEW
(4297)      IF(PNEW-F(1)) 370,382,380
(4298) C     LOWER-BOUND RESET
(4299) 370   IF(Q3.EQ.F(1)) GO TO 371
(4300)      IF(Q3.EQ.F(NF)) GO TO 371
(4301)      C9=C9*(F(1)-Q3)/P8
(4302)      P10=F(1)
(4303)      IF (IGEN.GT.0) GO TO 382
(4304)      WRITE(KW,1080)
(4305) 1080  FORMAT(/18H LOWER-BOUND RESET)
(4306) 382   KP19=1
(4307) 371   C5=C5+C9*SLOW
(4308)      GO TO 120
(4309) 380   IF(PNEW-F(NF)) 382,382,385
(4310) 385   IF(Q3.EQ.F(NF)) GO TO 371
(4311)      IF(Q3.EQ.F(1)) GO TO 371
(4312)      C9=C9*(F(NF)-Q3)/P8
(4313)      P10=F(NF)
(4314)      IF (IGEN.GT.0) GO TO 382
(4315)      WRITE(KW,1090)
(4316) 1090  FORMAT(/18H UPPER-BOUND RESET)
(4317)      GO TO 382
(4318) 393   IF (IGEN.LT.0) WRITE (KW,1085) KP9,K05
(4319) 1085  FORMAT(/27H0ITERATION OSCILLATES AFTER,I3,17H TRIALS FOR ROOT#,I3)
(4320)      GO TO 500
(4321) 3931  KDOWN = 0
(4322)      IDOWN = 0
(4323)      GO TO 243
(4324) 394   IF (IGEN.LT.0) WRITE (KW,499)
(4325) 499   FORMAT (/45H AFTER 20 ITERATIONS, NO EIGENVALUE IS FOUND /)
(4326)      GO TO 500
(4327) C     COMPUTE FACTORIZATION FUNCTIONS
(4328) 395   IF(K05.GE.K5MAX) GO TO 5001
(4329)      DO 400 K=1,NF
(4330)      R9 = (F(K)-Q2(K05M))*(F(K)+Q2(K05M))/FSQ(K)*39.478417
(4331)      A1(K05M,K) = R9*AM8(K05M)
(4332) 400   CONTINUE
(4333)      GO TO 101
(4334) C     COMPUTE EIGENVECTORS
(4335) 500   JBEG = 1
(4336)      GO TO 101
(4337) 5001  IF (IS.EQ.1) GO TO 503
(4338)      IF (IROT.EQ.2) GO TO 502
(4339)      WRITE(KW,1092) K05M
(4340) 1092  FORMAT (1H1,32HNUMBER OF CD -ROTATIONAL MODES =,I3)
(4341)      GO TO 503

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(4342) 502 WRITE(KW,1093) K05M
(4343) 1093 FORMAT (1H1,32HNUMBER OF CTR-ROTATIONAL MODES =,13)
(4344) 503 CONTINUE
(4345) IF (K05M.EQ.0) GO TO 805
(4346) C REORDER EIGENVALUES
(4347) DO 510 M=1,K05M
(4348) IF (M.EQ.K05M) GO TO 510
(4349) AMIN = Q2(M)
(4350) INDEX = M
(4351) MP1 = M+1
(4352) DO 505 N=MP1,K05M
(4353) IF (AMIN.LE.Q2(N)) GO TO 505
(4354) INDEX = N
(4355) AMIN = Q2(N)
(4356) 505 CONTINUE
(4357) IF (INDEX.EQ.M) GO TO 510
(4358) SWAP = Q2(M)
(4359) Q2(M) = Q2(INDEX)
(4360) Q2(INDEX) = SWAP
(4361) SWAP = B(M)
(4362) B(M) = B(INDEX)
(4363) B(INDEX) = SWAP
(4364) SWAP = AM8(M)
(4365) AM8(M) = AM8(INDEX)
(4366) AM8(INDEX) = SWAP
(4367) SWAP = AM9(M)
(4368) AM9(M)=AM9(INDEX)
(4369) AM9(INDEX)=SWAP
(4370) SWAP = AM7(M)
(4371) AM7(M)=AM9(INDEX)
(4372) AM7(INDEX)=SWAP
(4373) SWAP=EO(M)
(4374) EO(M)=EO(INDEX)
(4375) EO(INDEX)=SWAP
(4376) 510 CONTINUE
(4377) DO 800 M=1,K05M
(4378) C LOCATE FREQUENCY INTERVAL
(4379) DO 515 K=2,MF
(4380) IF (Q2(M).LT.F(K)) GO TO 520
(4381) 515 CONTINUE
(4382) K0 = MF
(4383) GO TO 525
(4384) 520 K0 = K-1
(4385) 525 K02 = 2*K0
(4386) K01 = K02-1
(4387) DF = Q2(M)-F(K0)
(4388) C CALCULATE INTERPOLATED MATRIX ELEMENTS
(4389) REWIND KE
(4390) C50=Q2(M)*AC5(M)
(4391) N1 = 1
(4392) N2 = NB
(4393) DO 576 L=1,2
(4394) IF (IS.EQ.0.AND.L.NE.IROT) GO TO 576
(4395) MB = (L-1)*NB

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(4396)      LB = (2*L-3)*NB
(4397)      DO 575 I=N1,N2
(4398)      IO = I+NB
(4399)      IO2 = 2*IO
(4400)      IO1 = IO2-1
(4401)      I1 = IO-LB
(4402)      I12 = 2*I1
(4403)      I11 = I12-1
(4404)      DO 570 J=I,N2
(4405)      JO = J+NB
(4406)      JO2 = 2*JO
(4407)      JO1 = JO2-1
(4408)      J1 = JO-LB
(4409)      J12 = 2*J1
(4410)      J11 = J12-1
(4411)      READ (KE) ((ULX(K),K=1,MF2),((Z1(IA,K),Z2(IA,K)),IA=1,3),K=1,MF)
(4412)      A1LX1 = 0.0
(4413)      A1LX2 = 0.0
(4414)      IF (DF.EQ.0.) GO TO 555
(4415)      DO 550 K=1,3
(4416)      K1 = 4-K
(4417)      A1LX1 = DF*(A1LX1+Z1(K1,K0))
(4418) 550    A1LX2 = DF*(A1LX2+Z2(K1,K0))
(4419) 555    TABLX(IO,JO1) = A1LX1+ULX(K01)
(4420)      TABLX(IO,JO2) = A1LX2+ULX(K02)
(4421)      YLX(IO,JO1) = TABLX(IO,JO1)
(4422)      IF (I.NE.J) GO TO 557
(4423)      YLX(IO,JO2) = TABLX(IO,JO2)-C50
(4424)      GO TO 570
(4425) 557    YLX(IO,JO2) = TABLX(IO,JO2)
(4426)      TABLX(JO,IO1) = TABLX(IO,JO1)
(4427)      TABLX(JO,IO2) = TABLX(IO,JO2)
(4428)      YLX(JO,IO1) = YLX(IO,JO1)
(4429)      YLX(JO,IO2) = YLX(IO,JO2)
(4430)      TABLX(IO,J11) = 0.0
(4431)      TABLX(IO,J12) = 0.0
(4432)      TABLX(JO,I11) = 0.0
(4433)      TABLX(JO,I12) = 0.0
(4434)      YLX(IO,J11) = 0.0
(4435)      YLX(IO,J12) = 0.0
(4436)      YLX(JO,I11) = 0.0
(4437)      YLX(JO,I12) = 0.0
(4438) 570    CONTINUE
(4439)      IF (IS.EQ.0) GO TO 575
(4440)      READ (KE) ((ULX(K),K=1,MF2),((Z1(IA,K),Z2(IA,K)),IA=1,3),K=1,MF)
(4441)      A1LX1 = 0.0
(4442)      A1LX2 = 0.0
(4443)      IF (DF.EQ.0) GO TO 574
(4444)      DO 573 K=1,3
(4445)      K1 = 4-K
(4446)      A1LX1 = DF*(A1LX1+Z1(K1,K0))
(4447) 573    A1LX2 = DF*(A1LX2+Z2(K1,K0))
(4448) 574    TABLX(IO,I11) = A1LX1+ULX(K01)
(4449)      TABLX(IO,I12) = A1LX2+ULX(K02)

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(4450)      YLX(10,111) = TABLX(10,111)
(4451)      YLX(10,112) = TABLX(10,112)
(4452) 575   CONTINUE
(4453) 576   CONTINUE
(4454)      IF (JDG.NE.6) GO TO 578
(4455)      DO 577 I=1,N20
(4456)      IROW(I) = I
(4457)      ICOL(I) = I
(4458) 577   CONTINUE
(4459)      WRITE (KW,1001)
(4460) 1001  FORMAT (23H1MODE SHAPE DIAGNOSTICS//19H MODIFIED IMPEDANCE)
(4461)      CALL MOUTC(YLX,N20,N20,M6,JR,JR,IROW,ICOL,LINE,KW)
(4462)  C      CALCULATE CHARACTERISTIC VECTOR
(4463)  C      INVERT MODIFIED IMPEDANCE
(4464) 578   N2 = NB+IS*NB
(4465)      ID=1
(4466)      CALL PINVC(ID,KW,NB,N40,N40,IS,IROT,YLX,JDG)
(4467)      IF (JDG.NE.6) GO TO 580
(4468)      DO 579 I=1,N20
(4469)      IROW(I) = I
(4470)      ICOL(I) = I
(4471) 579   CONTINUE
(4472)      WRITE (KW,1002)
(4473) 1002  FORMAT (/30H INVERSE OF MODIFIED IMPEDANCE)
(4474)      CALL MOUTC(YLX,N20,N20,M6,JR,JR,IROW,ICOL,LINE,KW)
(4475)      WRITE (KW,1091)
(4476)  C      SEARCH FOR LARGEST ELEMENT
(4477) 580   KMAX = 0
(4478)      DO 606 K=1,N2
(4479)      DO 606 I=1,N2
(4480)      I2 = 2*I
(4481)      I1 = I2-1
(4482)      IF (K9(I).EQ.2) GO TO 606
(4483)      TRY = YLX(K,I1)**2+YLX(K,I2)**2
(4484)      IF (KMAX.EQ.1) GO TO 602
(4485)      KMAX = 1
(4486)      GO TO 604
(4487) 602   IF (TRY.LE.AMAX) GO TO 606
(4488) 604   AMAX = TRY
(4489)      IX = I
(4490)      KX = K
(4491) 606   CONTINUE
(4492)  C      NORMALIZATION:
(4493)      IX2 = 2*IX
(4494)      IX1 = IX2-1
(4495)      DLX(1) = YLX(KX,IX1)
(4496)      DLX(2) = YLX(KX,IX2)
(4497)      DLO = DLX(1)**2+DLX(2)**2
(4498)      LB = (2*IROT-3)*NB
(4499)      MB = (IROT-1)*NB
(4500)      DO 720 I=1,N2
(4501)      IO = I
(4502)      IF (IS.EQ.1) GO TO 718
(4503)      IO = IO+MB

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(4504)      I1 = IO-LB
(4505)      I12 = 2*I1
(4506)      I11 = I12-1
(4507)      WLX(I11) = 0.0
(4508)      WLX(I12) = 0.0
(4509) 718   I02 = 2*IO
(4510)      I01 = I02-1
(4511)      WLX(I01) = (YLX(IO,IX1)*DLX(1)+YLX(IO,IX2)*DLX(2))/CLO
(4512)      WLX(I02) = (YLX(IO,IX2)*DLX(1)-YLX(IO,IX1)*DLX(2))/DLO
(4513) 720   CONTINUE
(4514) C     RESPONSE/MODE-SHAPE TABULATION
(4515)      IOR = 0
(4516)      JOR = 0
(4517)      IFLAG = 0
(4518)      IF (IRUN.EQ.2) SPD = Q2(M)
(4519)      RPM = 60.0*SPD
(4520) 722   DO 725 I=1,NB
(4521)      I2 = 2*I
(4522)      I1 = I2-1
(4523)      L = I+NB
(4524)      L2 = 2*L
(4525)      L1 = L2-1
(4526) 725   CALL ORBIT(IOR,BIG(I),SMALL(I),SLANT(I),PHASE(I),WLX(I1),WLX(I2),
(4527)      +                               WLX(L1),WLX(L2))
(4528)      IF (IFLAG.EQ.0) GO TO 727
(4529)      WRITE (KW,1011)
(4530) 1011  FORMAT (///18H RESONANT RESPONSE)
(4531)      IF (IT.EQ.0) GO TO 1016
(4532)      CALL XCITAB(KW,IT,NB,M8,K8,PLX)
(4533)      WRITE (KW,1012)
(4534) 1012  FORMAT (///15H RESPONSE ORBIT/)
(4535)      GO TO 728
(4536) 1016  CALL XCITAB(KW,IT,NB,M8,K8,ALX)
(4537)      WRITE (KW,1012)
(4538)      GO TO 728
(4539) 727   IF (IRUN.EQ.4.OR.M.EQ.1) WRITE (KW,1091)
(4540)      WRITE (KW,1015) RPM,Q2(M),B(M),AM9(M)
(4541) 1015  FORMAT(19HOROTATIONAL SPEED =,1PE11.4,4H RPM/17H FREQUENCY
(4542)      +,2H =,E11.4,4H HZ/19H CRIT DAMP RATIO =,E11.4/
(4543)      +19H PRECISION INDEX =,E11.4)
(4544)      WRITE (KW,1110)
(4545) 1110  FORMAT (19H NATURAL MODE SHAPE)
(4546) 728   CALL ORBTAB(KW,NB,M8,K8,SPD,Q2(M),BIG,SMALL,SLANT,PHASE,POSIT,JOR)
(4547)      IF (IFLAG.GT.0.OR.IRUN.EQ.5) GO TO 800
(4548) C     RESONANT RESPONSE
(4549)      IFLAG = 1
(4550) C     FORCE INTERPOLATION
(4551)      DO 756 I=1,N20
(4552)      I2 = 2*I
(4553)      I1 = I2-1
(4554)      IF (IRUN.EQ.2.AND.I.GT.NB) GO TO 755
(4555)      REWIND KS
(4556)      DO 752 K=1,NF
(4557)      K2 = 2*K

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(4558)      K1 = K2-1
(4559)      READ(KS) SPD, FRE, ((YLX(II, J1), J1=1, N202), II=1, N20)
(4560)      READ (KS) (WLX(II), II=1, N202)
(4561)      ULX(K1) = WLX(I1)
(4562) 752   ULX(K2) = WLX(I2)
(4563)      DO 753 K=1, NF
(4564)      K1 = 2*K-1
(4565) 753   Y(K) = ULX(K1)
(4566)      XINT(1) = Q2(M)
(4567)      IER = 0
(4568)      CALL SPLINE (ISP, NF, RET, XINT, F, Y, Z1, KW, IER)
(4569)      IF (IER.NE.0) GO TO 806
(4570)      REP = RET(1)
(4571)      DO 754 K=1, NF
(4572)      K2 = 2*K
(4573) 754   Y(K) = ULX(K2)
(4574)      IER = 0
(4575)      CALL SPLINE (ISP, NF, RET, XINT, F, Y, Z2, KW, IER)
(4576)      IF (IER.NE.0) GO TO 806
(4577)      PLX(I1) = REP
(4578)      PLX(I2) = RET(1)
(4579)      GO TO 756
(4580) 755   PLX(I1) = 0.0
(4581)      PLX(I2) = 0.0
(4582) 756   CONTINUE
(4583)  C      ENSURE WHIRL REPRESENTATION
(4584)      DO 765 I=1, NB
(4585)      I2 = 2*I
(4586)      I1 = I2-1
(4587)      L = I+NB
(4588)      L2 = 2*L
(4589)      L1 = L2-1
(4590)      IF (IT.EQ.1) GO TO 760
(4591)      ALX(I1) = PLX(I1)
(4592)      ALX(I2) = PLX(I2)
(4593)      ALX(L1) = PLX(L1)
(4594)      ALX(L2) = PLX(L2)
(4595)      GO TO 765
(4596) 760   ALX(I1) = 0.5*PLX(I1)
(4597)      ALX(I2) = 0.5*PLX(I2)
(4598)      ALX(L1) = ALX(I1)
(4599)      ALX(L2) = ALX(I2)
(4600)      DLX(1) = -0.5*PLX(L2)
(4601)      DLX(2) = 0.5*PLX(L1)
(4602)      ALX(I1) = ALX(I1)+DLX(1)
(4603)      ALX(I2) = ALX(I2)+DLX(2)
(4604)      ALX(L1) = ALX(L1)-DLX(1)
(4605)      ALX(L2) = ALX(L2)-DLX(2)
(4606) 765   CONTINUE
(4607)  C      RESPONSE CALCULATION
(4608)      IF (JDG.NE.6) GO TO 769
(4609)      DO 767 I=1, N20
(4610)      IROW(I) = I
(4611)      ICOL(I) = I

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(4612) 767 CONTINUE
(4613) WRITE (KW,1003)
(4614) 1003 FORMAT (21H1RESPONSE DIAGNOSTICS//23H INTERPOLATED IMPEDANCE)
(4615) CALL MOUTC(TABLX,N20,N20,M6,JR,JR,IROW,ICOL,LINE,KW)
(4616) C INVERT IMPEDANCE MATRIX
(4617) 769 ID = 1
(4618) CALL PINVC(ID,KW,NB,N40,N40,IS,IROT,TABLX,JDG)
(4619) IF (JDG.NE.6) GO TO 762
(4620) DO 768 I=1,N20
(4621) IROW(I) = I
(4622) ICOL(I) = I
(4623) 768 CONTINUE
(4624) WRITE (KW,1004)
(4625) 1004 FORMAT (/34H INVERSE OF INTERPOLATED IMPEDANCE)
(4626) CALL MOUTC(TABLX,N20,N20,M6,JR,JR,IROW,ICOL,LINE,KW)
(4627) WRITE (KW,1091)
(4628) 762 DO 770 I=1,NB
(4629) I2 = 2*I
(4630) I1 = I2-1
(4631) L = I+NB
(4632) L2 = 2*L
(4633) L1 = L2-1
(4634) WLX(I1) = 0.0
(4635) WLX(I2) = 0.0
(4636) WLX(L1) = 0.0
(4637) WLX(L2) = 0.0
(4638) DO 770 J=1,NB
(4639) J2 = 2*J
(4640) J1 = J2-1
(4641) K = J+NB
(4642) K2 = 2*K
(4643) K1 = K2-1
(4644) WLX(I1)=WLX(I1)+TABLX(I,J1)*ALX(J1)-TABLX(I,J2)*ALX(J2)
(4645) WLX(I2)=WLX(I2)+TABLX(I,J2)*ALX(J1)+TABLX(I,J1)*ALX(J2)
(4646) IF (IS.EQ.0) GO TO 766
(4647) WLX(L1)=WLX(L1)+TABLX(L,J1)*ALX(J1)-TABLX(L,J2)*ALX(J2)
(4648) WLX(L2)=WLX(L2)+TABLX(L,J2)*ALX(J1)+TABLX(L,J1)*ALX(J2)
(4649) IF (IRUN.EQ.2) GO TO 770
(4650) WLX(I1)=WLX(I1)+TABLX(I,K1)*ALX(K1)-TABLX(I,K2)*ALX(K2)
(4651) WLX(I2)=WLX(I2)+TABLX(I,K2)*ALX(K1)+TABLX(I,K1)*ALX(K2)
(4652) 766 WLX(L1)=WLX(L1)+TABLX(L,K1)*ALX(K1)-TABLX(L,K2)*ALX(K2)
(4653) WLX(L2)=WLX(L2)+TABLX(L,K2)*ALX(K1)+TABLX(L,K1)*ALX(K2)
(4654) 770 CONTINUE
(4655) GO TO 722
(4656) 800 CONTINUE
(4657) 805 IF (IROT.EQ.2.OR.IRUN.EQ.2) GO TO 810
(4658) IROT = 2
(4659) GO TO 100
(4660) 806 WRITE (KW,1200)
(4661) 1200 FORMAT (/49H ERROR ENCOUNTERED DURING EXECUTION OF SUBROUTINE,
(4662) +8H SPLINE.)
(4663) CALL EXIT
(4664) 810 CONTINUE
(4665) RETURN
(4666) END

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